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COUPON AND BIRDSTRIKE TESTING OF F-111 ADBIRT WINDSHIELDS WHICH HAVE BEEN SUBJECTED TO SIMULATED PRESSURE/ THERMAL SERVICE LIFE

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This program consisted of birdstrike testing, crack analysis, and coupon testing of F-111 ADBIRT windshield transparencies which had been subjected to pressure/thermal testing in the WPAFB Building 68 Transparency Durability Facility. Three pairs of F-111 ADBIRT windshield transparencies (left and right hand) were used in this program, one pair each from Sierracin/Sylmar Corp., Swedlow, Inc., and PPG Industries, Inc. The edges and bolt holes of all of the transparencies were examined for edge cracking. The three right-hand windshields were birdstrike tested, and the three left hand windshields were used for coupon testing. Dynamic mechanical analysis (DMA), gel permeation chromatography (GPC), tensile, and edge attachment testing were conducted. Simulated service life in the durability facility did not produce as much structural degradation in terms of birdstrike resistance as in-service aging. A significant number of cracks were found in the windshields in the vicinity of the edge attachments, similar to cracking from in-service aged windshields. Coupon testing revealed no bulk polycarbonate degradation.

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PREFACE

The efforts reported herein were performed by the Aerospace Mechanics Division of the University of Dayton Research Institute (UDRI), Dayton, Ohio, under Air Force Contract F33615-84-C-3404, modification P00011. The program was sponsored by the Wright Laboratory, Flight Dynamics Directorate, Wright-Patterson Air Force Base, Ohio. Air Force administrative direction and technical support were provided by Mr. Russ Urzi, of WL/FIVR.

The work described herein was conducted during the period February 1990 to October 1990. University of Dayton project supervision was provided by Mr. Dale H. Whitford, Supervisor, Aerospace Mechanics Division, and Mr. Blaine S. West, Head, Structures Group. Mr. Daniel R. Bowman was the principal investigator.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (continued)

LIST OF TABLES

SECTION 1
INTRODUCTION

1.1 BACKGROUND

The U.S. Air Force, recognizing the importance of maintaining bird impact resistance protection for its pilots and recognizing that high performance aircraft transparencies are a high cost item, is committed to continued monitoring, testing, and evaluation of aircraft transparencies.

In 1984, under contract No. F33615-84-C-3403, project 1926, the Wright Laboratory contracted with the UDRI to conduct a program to test service-aged F-111 transparencies. The main objective of that program was to determine the effect of in-service* aging on bird impact resistance capability. The program was conducted from May 1985 to December 1987 and included 22 full-scale birdstrike tests of baseline and in-service aged windshields. Reference 1 gives a complete discussion of this subject.

The structural integrity of in-service aged F-111 ADBIRT windshields was found to be significantly reduced by in-service aging. Results of the bird impact tests indicated that the windshield capability is reduced from a 470 knot baseline capability (as tested on simulated flight hardware) to 360 knots after 2 years in-service aging (40% in terms of impact energy), and reaches an asymptotic minimum value of 325 knots at an installed age of 5 years. Birdstrike risk assessment of the windshield indicated that, given a birdstrike, degradation causes the likelihood of penetration to increase significantly with installed age.

The reduction of bird impact resistance capability with installed age caused Air Force concern. As a result, the Air Force contracted with UDRI (Contract F33615-84-C-3404, modification P00011) to conduct additional research of the F-111 windshield structural degradation problem. The program consisted of laboratory coupon tests of in-service aged and baseline F-111 ADBIRT windshield coupons; research of polycarbonate degradation and craze testing; fractography; and finite element analysis of the windshield edge attachment.

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* In-service age is defined as the amount of time the transparency was on the aircraft, also referred to as installed age.

Coupon testing indicated no polycarbonate degradation. Analysis of the edge attachment revealed numerous fatigue cracks at the edges and in the vicinity of the bolt holes. We believe that these fatigue cracks were the direct cause of the reduction in birdstrike resistance of in-service aged windshields. Finite element analysis showed significant tensile stresses at the edges for various pressure/thermal load cases. These stresses were high enough to propagate existing cracks, and in several cases the stresses were high enough to initiate cracks. Craze testing of the sealants, cleaners, and other chemicals used to install or clean aircraft windshields indicated that many of the substances which are used in conjunction with aircraft transparencies cause crazing of polycarbonate. This crazing, in conjunction with the cyclic in-service pressure/thermal loads, was considered to be the most likely initiator of the fatigue cracks in F-111 ADBIRT windshields. A complete discussion of the results of that program may be found in Reference 2.

1.2 OBJECTIVES

The objectives of this program are:

(1) To determine if F-111 ADBIRT windshield transparencies subjected to simulated service life testing in the WPAFB Full-Scale Durability Facility are experiencing structural degradation similar to in-service aged windshields, and

(2) To gain additional insight into the cause of edge attachment cracking and subsequent structural degradation of in-service aged F-111 ADBIRT windshield transparencies.

1.3 SCOPE

This program included an experimental coupon test phase, edge attachment crack analysis, and full-scale birdstrike testing. Laboratory coupon tests were chosen to analyze windshield degradation causes and effects. Sections 2 and 3 summarize laboratory coupon tests of the F-111 ADBIRT windshields. The edge attachment crack analysis is summarized in Section 4. The birdstrike testing is summarized in Section 5. Conclusions and recommendations are presented in Section 6.

SECTION 2

TEST ARTICLE, COUPON TEST MATRIX, AND SPECIMEN PREPARATION

2.1 TEST ARTICLE PROCUREMENT FOR EXPERIMENTAL STUDIES

Six F-111 ADBIRT windshields were used for this program. These windshields were previously used for pressure/thermal testing in the WPAFB Full-Scale Durability Facility. Figure 2.1 presents the nominal cross section for each transparency manufacturer. Table 2.1 is a list of the windshields used in this program and includes a brief summary of the test history for each set of transparencies.

2.2 TEST MATRIX

This program was based on a coupon test matrix of 93 specimens, as shown in Table 2.2. The experimental coupon tests were chosen based on the results of the Reference 2 program.

2.3 SPECIMEN LAYOUT AND FABRICATION

The dynamic mechanical analysis (DMA), gel permeation chromatography (GPC), and tensile coupon specimens were fabricated from material near the center of the windshields away from the edges. The tensile edge attachment coupon specimens were fabricated from material along the aft arch of the windshields. Only the left-hand windshields were used for coupon testing; the right-hand windshields were used for birdstrike testing. All specimen fabrication was accomplished in the UDRI machine shop. Specimens were first cut from the full-size transparencies by jig-sawing and/or band-sawing. Selected edges of specimens, such as edge attachment sides, were milled as necessary. Cutting temperature was controlled during milling, when required, through the use of cooling air. Edges were machined dry in a vertical mill using a four-flute 1-inch diameter cutter at 900 RPM and a table feed of 6-1/2 inches/minute. Care was taken to minimize heat-up by removing less than 0.030-inch of material per cut.

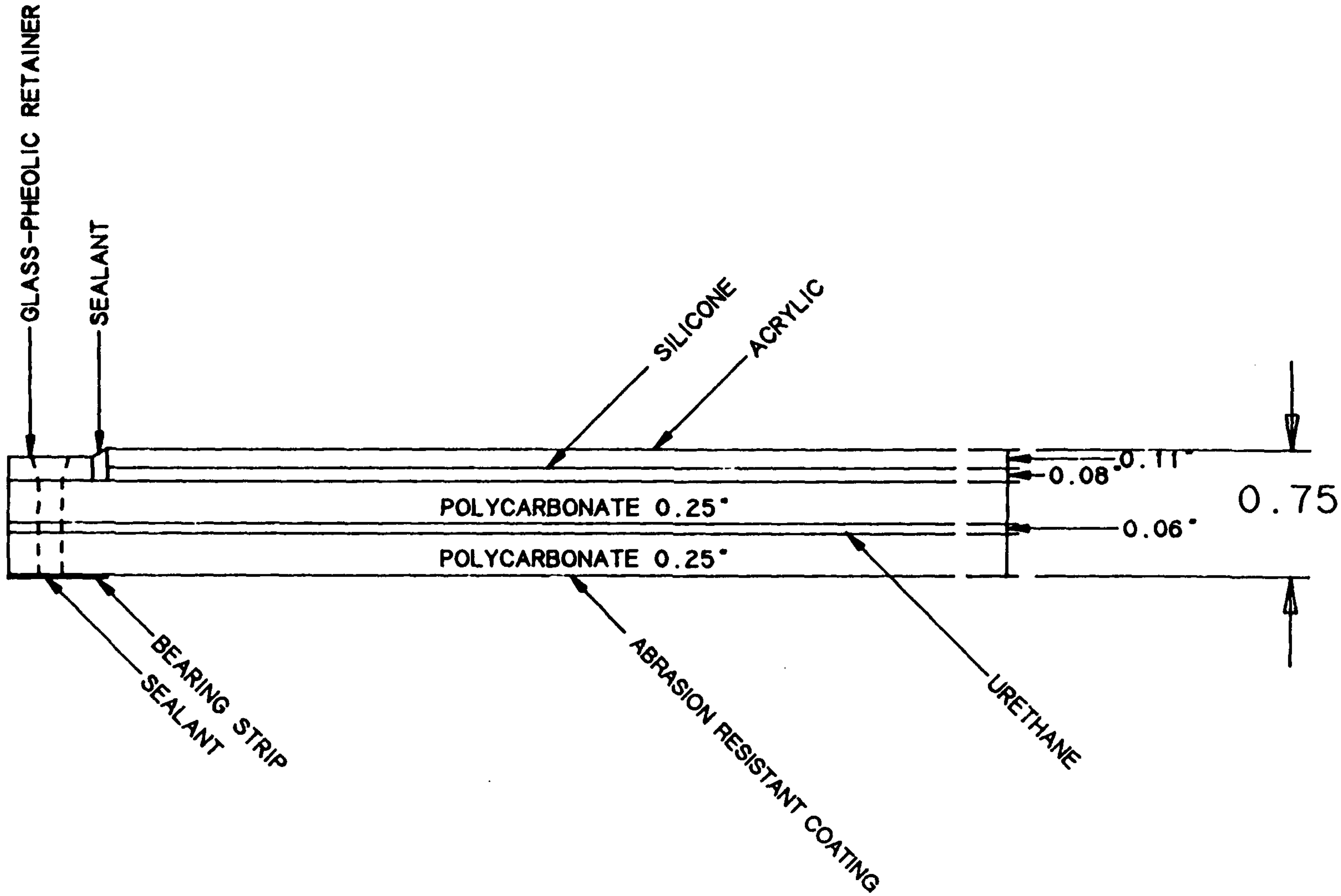


Figure 2.1. F-111 ADBIRT Transparency Nominal Cross-Section.

TABLE 2.1

TEST TRANSPARENCIES

MANUFACTURER/ SERIAL NUMBER	WINDSHIELD	DATE OF MANUFACTURE	SIMULATED SERVICE LIFE	CROSS-SECTION
PPG SN 87-H-04-20-2380	left	4/87	156.12 flight* hours ≈6.25 mo.	gold coated AC/S/PC/U/PC
PPG SN 86-H-11-04-2010	right	11/86	156.12 flight* hours ≈6.25 mo.	gold coated AC/S/PC/U/PC
Swedlow SN 027	left		847.19 flight* hours ≈2y 9.9 mo	gold coated AC/S/PC/U/PC
Swedlow SN 018	right	2/86	847.19 flight* hours ≈2y 9.9 mo	gold coated AC/S/PC/U/PC
Sierracin SN 057	left	11/87	1225 flight hours ≈4y 1 mo.	gold coated AC/S/PC/U/PC
Sierracin SN 082	right	8/84	1225 flight hours ≈4y 1 mo.	AC/S/PC/U/PC

*Transparencies declared failures - unacceptable acrylic delamination.

AC - denotes acrylic   S - denotes silicone

PC - denotes polycarbonate   U - denotes urethane

TABLE 2.2
COUPON TEST MATRIX

TEST	NUMBER OF COUPONS PPG SN 87-H-84-20-2380	SWEDLOW SN 027	SIERRACIN SN 057
Tensile Edge Attachment	6	6	6
Tensile	20	20	20
Dynamic Mechanical Analysis (DMA)	3	3	3
Gel Permeation Chromatography (GPC)	2	2	2

TOTAL 93 COUPONS

SECTION 3
EXPERIMENTAL TESTS

3.1 TENSILE EDGE ATTACHMENT TESTS

3.1.1 Test Objective

The objective of this test was to evaluate tensile edge attachment strength. Edge attachment structural integrity is necessary for optimum bird impact resistance.

3.1.2 Specimen Configuration

The edge attachment beams were cut from the transparencies at the aft arch. The specimen geometry is shown in Figure 3.1.

3.1.3 Test Method

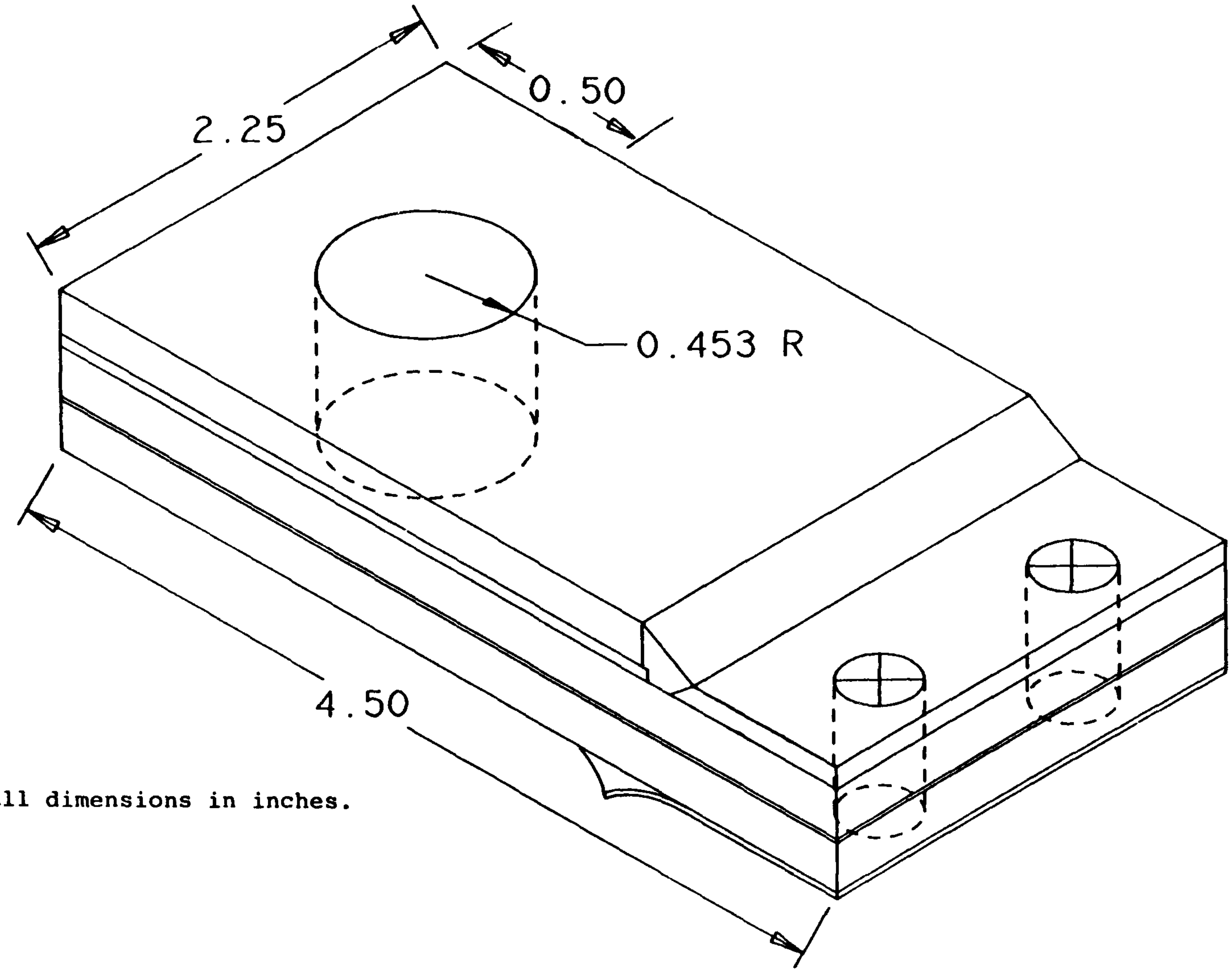
The edge attachment specimens were tested with the fastener end mounted in a fixture which simulated the attachments of the actual transparency design; the other end included a 0.9" diameter hole which was pin-loaded. The test fixture is shown in Figure 3.2. The test specimens were loaded in tension at a displacement rate of 500 in/min. using a electrohydraulic closed-loop MTS test machine. For all tests, load versus displacement data was stored in the digital memory of a transient recorder and played back at reduced speed on an X-Y recorder.

3.1.4 Test Data

Table 3.1 is a summary of the edge-attachment test data.

3.1.5 Data Analysis/Correlation

Swedlow coupons had much higher edge strength values than PPG or Sierracin. Those PPG and Sierracin specimens which exhibited brittle failure modes had pre-existing fatigue cracks before the test (some of which were not detected in the crack analysis of Section 4). Typically, those specimens with cracks had lower energy to failure values. In a birdstrike test, this would translate to lower birdstrike capability. Overall, these test results compare favorably with the results of previous testing conducted by UDRI (Reference 2) of coupons cut from in-service aged F-111 ADBIRT windshields. Failure energies for these tests ranged from 1519 to 2462 in.-lbs. Failure energies from the coupons cut from in-service aged windshields (tested previously) ranged from 146 to 2795 in.-lbs.



All dimensions in inches.

Figure 3.1. Tensile Edge Attachment Specimen.

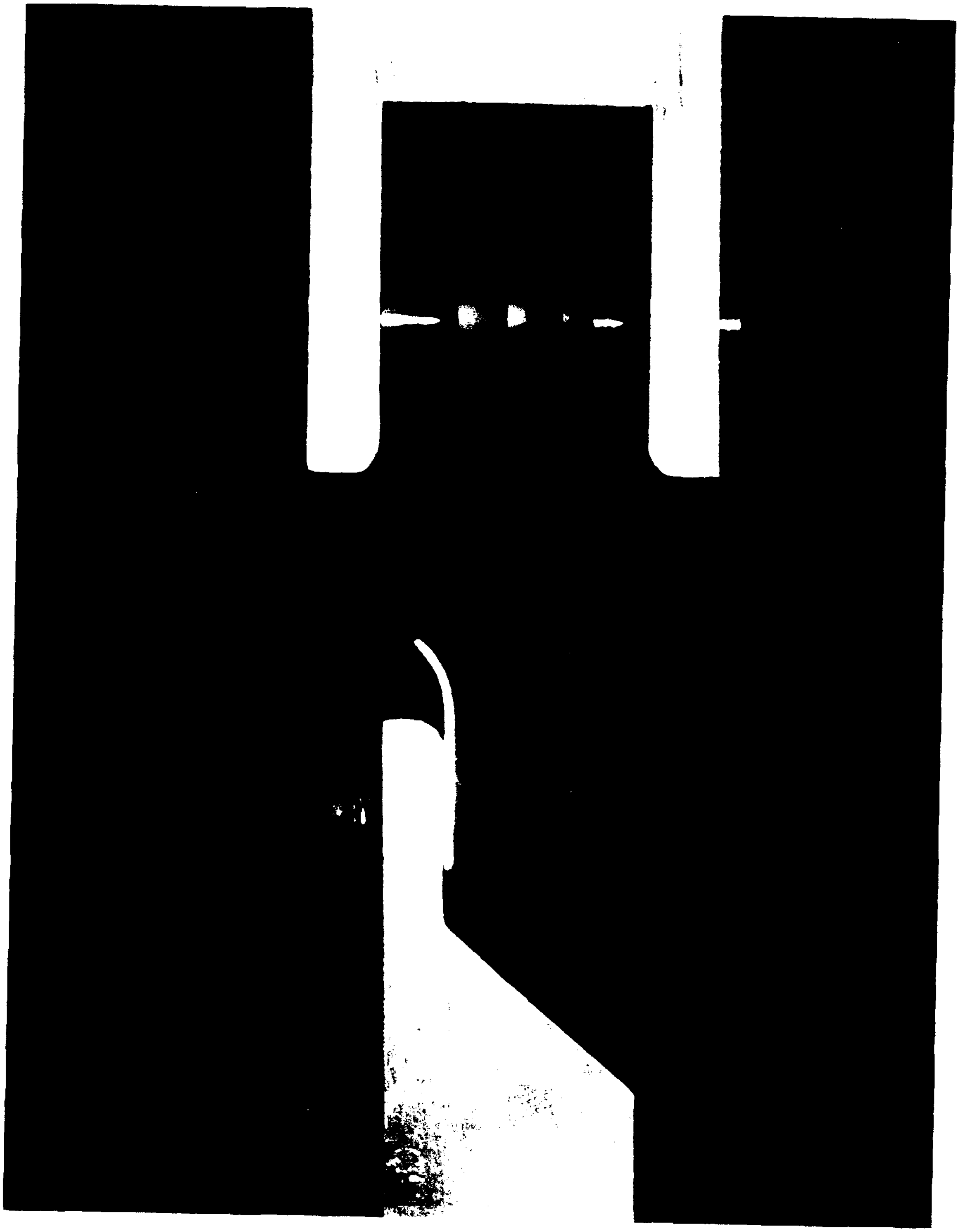


Figure 3.2 Tensile Edge Attachment Test Setup.

TABLE 3.1

TENSILE EDGE ATTACHMENT TEST RESULTS

Spec. ID	Manuf./ Serial#/ Time in Durability Facility	Peak Load (lb)	Average (lb)	Energy (in-lb)	Average (in-lb)	Failure Mode
1	Sierracin	3300		1656		DF, BH, CFMR
2	SN 057	3375		1538		DF/BF, BH, CFMR
3	1225 flight hours	3475	3471	1600	1519	DF, BH, CFMR, AFGPR/CFGPR
10		3400		1558		DF, BH, AFMR
17		3650		1302		DF/BF, AFGPR, AFMR
18		3625		1462		DF, AFGPR, AFMR
7	Swedlow	5075		2426		DF, BH, CFMR
8	SN 027	5175		2923		DF, BH, DMR
9	847 flight hours	4900	5108	2694	2462	DF, BH, CFMR/DFMR, DMR
11		5350		2532		DF, BH, CFMR/AFMR, DMR
15		5150		2252		DF, BS/BH, DMR
16		5000		1948		DF, BS/BH, DMR
4	PPG	3525		1139		BF, BH, CFMR/AFMR
5	SN 87-H-04-20-2380	3700		2008		DF, BH, AFMR
6	156 flight hours	3525	3824	1757	1767	DF/BF, BH, CFMR/DFMR
12		5120		2154		DF/BF, BH, CFMR, DMR
13		3525		1832		DF, BH, AFMR
14		3550		1709		DF, BH, CFMR/DFMR

Legend:

DF - Ductile failure of polycarbonate plies
BF - Brittle failure of polycarbonate plies
BS - Bolt shear
BH - Bolt head pulled through glass phenolic retainer
AFGPR - Adhesive failure of bond line between glass phenolic retainer and polycarbonate
CFGPR - Cohesive failure of bond line between glass phenolic retainer and polycarbonate
AFMR - Adhesive failure of bond line between metal retainer and polycarbonate
CFMR - Cohesive failure of bond line between metal retainer and polycarbonate
DFMR - Ductile failure of metal retainer
DMR - Ductile deformation of metal retainer

3.2 POLYCARBONATE TENSILE TESTS

3.2.1 Test Objective

The objective of this testing was to measure tensile properties of the bulk polycarbonate (structural ply). The tensile test is one of the most common measures of material performance; elongation and toughness are extremely important material characteristics for applications involving impact (such as birdstrike).

3.2.2 Specimen Configuration

The tensile test specimen is shown in Figure 3.3. These specimens were fabricated on a lathe. The 1/4-20 threads were machined with a radiused root to preclude the possibility of failure initiating at the thread root. Ten specimens were fabricated from each of the two polycarbonate structural plies from each windshield.

3.2.3 Test Method

The tensile testing was conducted using a MTS electrohydraulic closed-loop test machine. The tensile test setup is shown in Figure 3.4. The tensile tests were conducted using stroke control at a nominal actuator displacement rate of 5000 in/min. The corresponding nominal strain rate was 200 in/in/sec. The actual engineering strain rate achieved in the elastic portion of the tests was 131 in/in/sec. Actual engineering strain rate after yield was 232 in/in/sec. Load and crosshead displacement were measured. High-speed photography (5000 frame/sec) was used to obtain displacement data, providing more exact displacement data than had been obtained previously. Consequently, tensile modulus, strain rate, and elongation are also more exact than values generated from previous testing.

3.2.4 Test Data

Test data for the tensile tests are presented in Table 3.2. A typical load-displacement curve is shown in Figure 3.5. No linear portion of the load-displacement curve was observed during initial loading (at low strains) from which an initial elastic modulus could be obtained. However, the load displacement curves were fairly linear from test initiation up to 50% of the first peak load. Thus, the tensile modulus was calculated from that portion of the load displacement curve. Toughness (area under the load displacement curve) is presented in inch-pounds. Yield stress is the same as the tensile yield strength, and ultimate stress is the same as tensile strength at break, as defined in ASTM D 638.

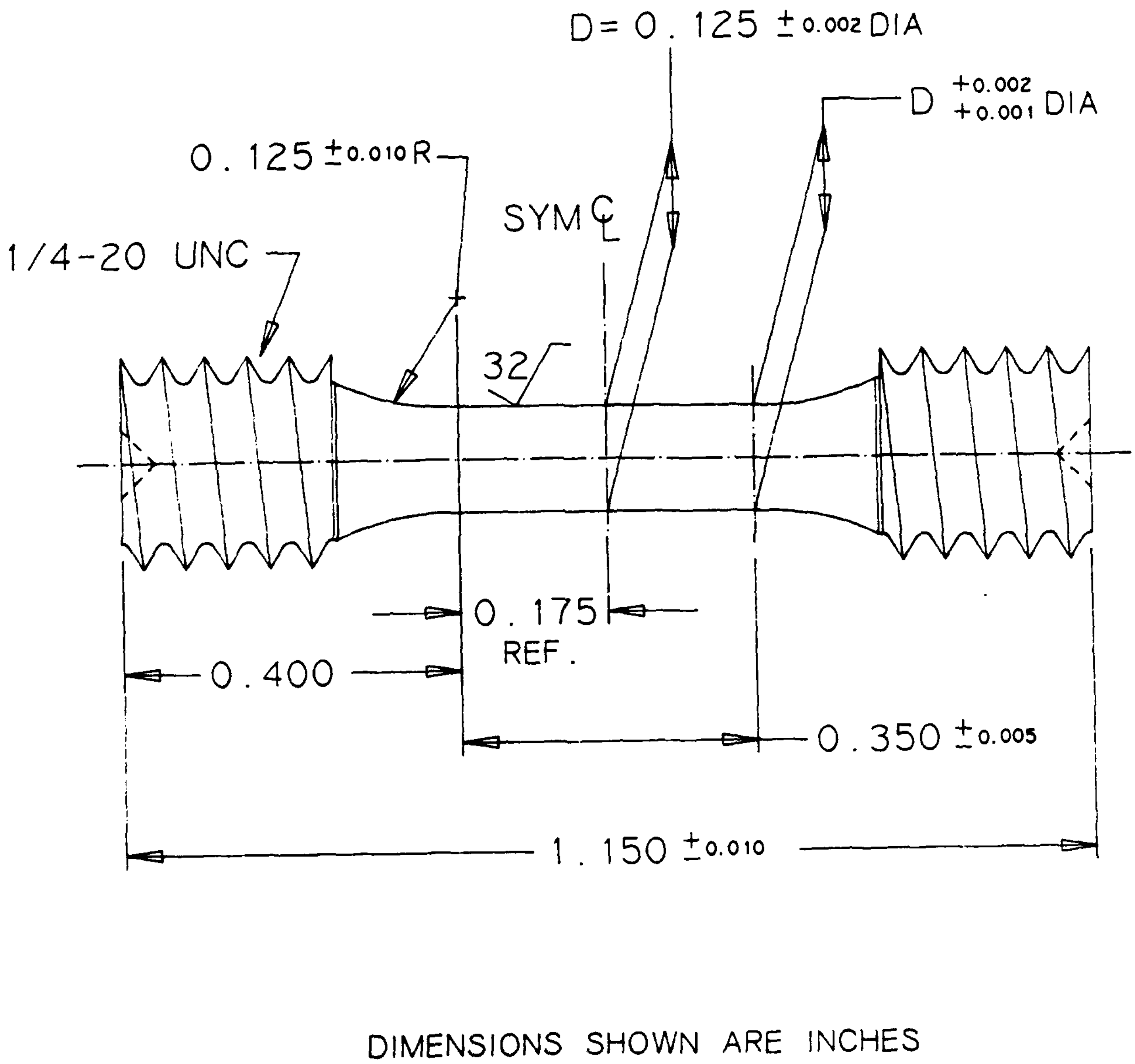


Figure 3.3 Tensile Test Specimen.

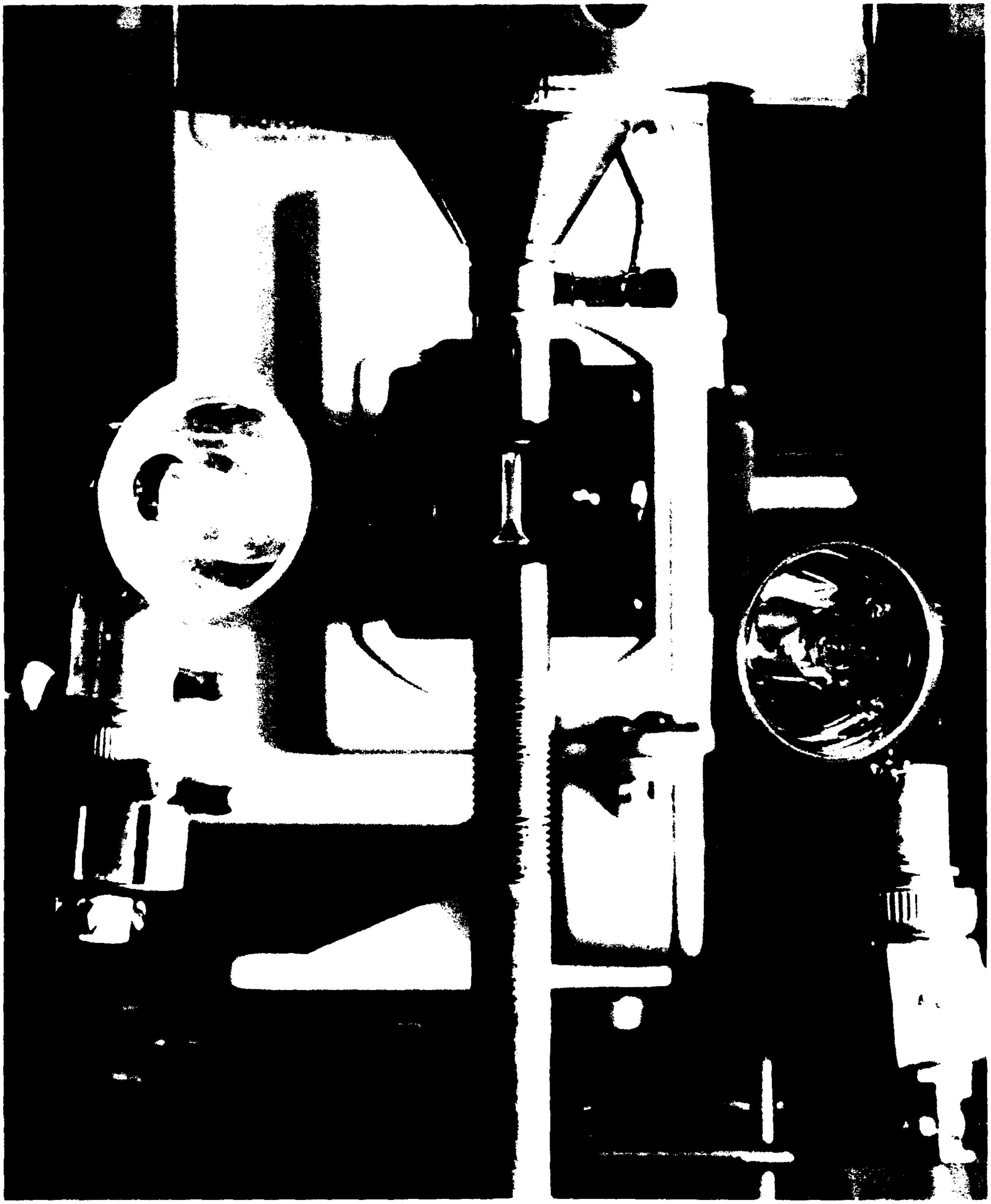


Figure 3.4. Tensile Test Setup.

TABLE 3.2

TENSILE TEST RESULTS

Manuf./ Serial#/ Time in Durability Facility	Ply	ID#	Diameter (in)	Tensile Modulus (psi)	Average (psi)	Yield Stress (psi)	Average (psi)	Ultimate Stress (psi)	Average (psi)	Energy (in-lb)	Average (in-lb)	Elongation (%)	Average (%)
PPG	INNER	1	0.125	961685		13598		12427		60.5		121.9	
SN 87-H-04-20-2380		2	0.1235	978253		13617		12626		60.8		133.8	
156 flight hours		3	0.124	857428		13249		12266		59.5		131.9	
		4	0.123	1426985		13518		12729		62.1		137.6	
		5	0.124	1379898	1088155	13249	13478	12628	12438	65.4	59.5	145.8	133.0
		6	0.123	1456714		13623		13045		****		*****	
		7	0.1245	1431979		13297		11603		51.2		117.4	
		8	0.1235	1125929		13409		12678		64.1		142.0	
		9	0.124	631340		13663		12473		60.5		133.2	
		10	0.124	631340		13560		11903		51.3			
	MIDDLE	1	0.1215	562597		14016		13692		56.4		127.1	
		2	0.123	557416		13255		12308		****		*****	
		3	0.123	728357		13571		12887		62.6		136.5	
		4	0.1245	644264		13554		12578		57.2		122.6	
		5	0.124	489424	622263	13456	13451	11075	12455	64.3	59.6	70.8	120.7
		6	0.124	704371		13249		11903		53.8		118.8	
		7	0.107	——		——		——		——		——	
		8	0.124	——		——		——		——		——	
		9	0.123	617369		13255		12361		57.6		128.3	
		10	0.1235	674306		13252		12835		65.1		140.9	
Swedlow	INNER	1	0.1255	618421		13743		12631		61.1		123.4	
SN 027		2	0.125	538481		13904		13140		****		*****	
847 flight hours		3	0.1245	730568		13656		12116		52.6		112.5	
		4	0.124	713354		13922		12783		61.6		130.8	
		5	0.124	844631	876494	13974	13784	13187	12212	65.1	54.8	137.1	116.9
		6	0.1255	454044		13692		12277		55.3		118.2	
		7	0.124	1358855		13870		10247		53.6		115.0	
		8	0.1245	1204935		13554		11141		36.0		81.5	
		9	0.125	1119422		13547		11714		46.0		101.1	
		10	0.1235	1182225		13983		12887		61.6		132.7	
	MIDDLE	1	0.123	686736		13518		12308		65.3		123.3	
		2	0.124	630442		13456		11903		52.1		115.0	
		3	0.124	511897		13456		12318		58.4		128.3	
		4	0.1235	626633		13565		12731		62.8		136.5	
		5	0.124	546024	615760	13456	13436	12835	12241	66.5	58.4	144.1	128.9
		6	0.1245	784454		13400		11551		47.7		106.2	
		7	0.1235	550454		13409		12522		60.4		132.7	
		8	0.124	605243		13456		12214		56.6		125.1	
		9	0.1245	552599		13451		11911		55.1		122.6	
		10	0.1245	663119		13194		12116		58.6		155.4	
Sierracin	INNER	1	0.124	563087		13560		12939		62.6		131.7	
SN 057		2	0.123	715871		13781		13571		66.6		141.7	
1225 flight hours		3	0.124	569913		13560		13094		67.0		141.7	
		4	0.1235	467481		13565		12104		48.0		105.6	
		5	0.1245	605726	594022	13451	13511	12835	12808	63.2	62.4	134.7	133.1
		6	0.1245	590888		13451		13246		66.7		141.0	
		7	0.123	534774		13676		12939		60.2		130.3	
		8	0.123	671297		13781		12361		64.9		137.2	
		9	0.124	610182		13508		12525		58.4		125.2	
		10	0.1235	611004		12783		12470		66.8		141.7	
	MIDDLE	1	0.124	578838		13249		13094		70.9		131.4	
		2	0.124	597214		13197		12990		69.7		150.4	
		3	0.123	652683		13360		12676		60.9		147.9	
		4	0.123	658154		13413		12939		65.3		141.5	
		5	0.1235	608397	593838	13461	13273	11478	12736	59.9	65.3	134.6	142.5
		6	0.124	492701		13146		12525		62.5		139.0	
		7	0.123	588631		13150		13202		69.8		152.9	
		8	0.1235	595443		13252		12783		63.4		140.3	
		9	0.124	542009		13146		12835		67.4		147.2	
		10	0.123	624306		13360		12834		63.5		140.3	

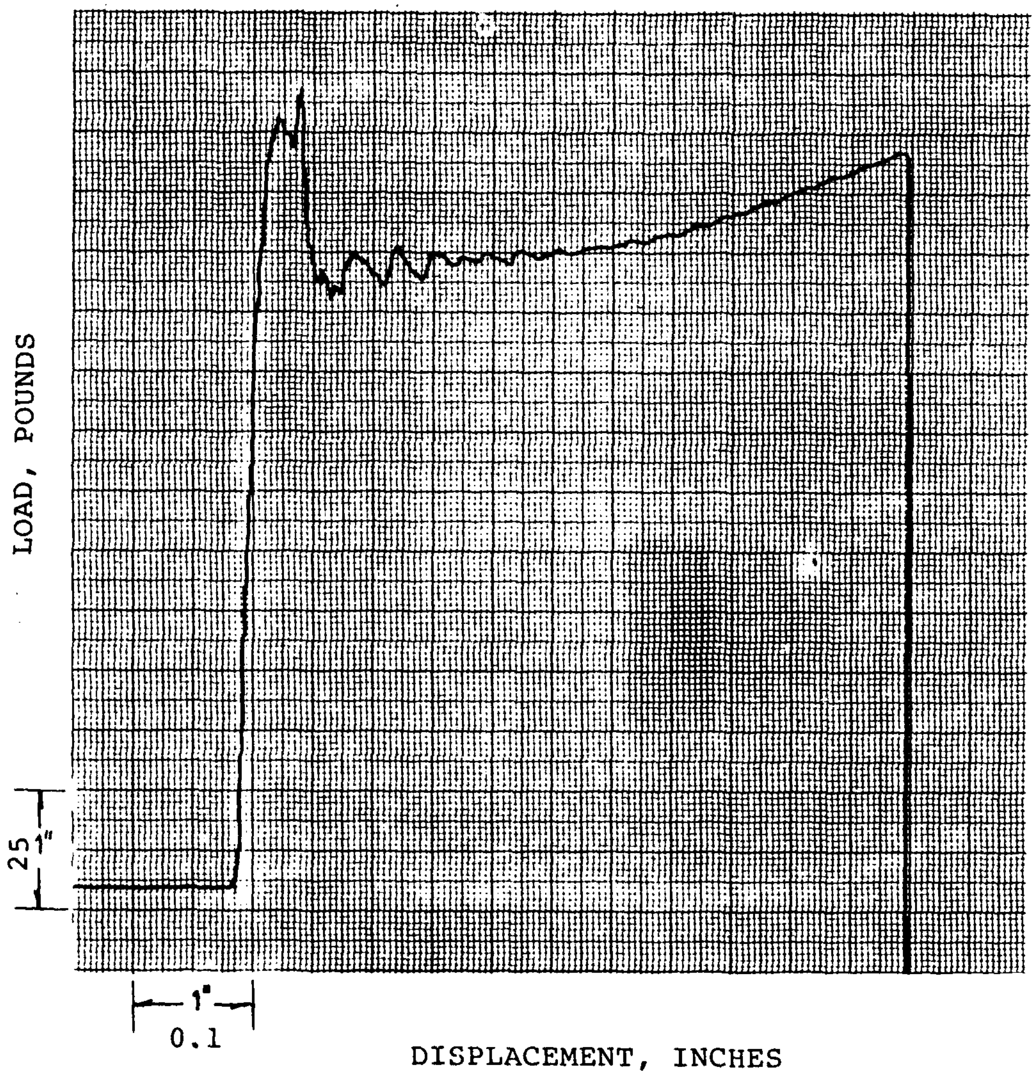


Figure 3.5. Typical Tensile Load-Displacement Curve.

3.2.5 Data Analysis/Correlation

The strain rates achieved in the high rate tensile testing are reasonably close to strain rates measured during birdstrike testing. These tests indicate that the bulk polycarbonate properties are not changing significantly. There are no obvious trends of increased yield strength with increased service aging in the durability facility (which is typically a characteristic of thermal aging); in addition, there does not appear to be any significant reduction in elongation or toughness. The initial elastic tensile modulus varies from 600,000 to 1,000,000 psi. This variation is due to the fact that the initial elastic tensile modulus is difficult to measure accurately, because of the rate of testing and fixture slack which is taken up at the initiation of the test.

3.3 DYNAMIC MECHANICAL ANALYSIS (DMA) TESTS

3.3.1 Test Objective

The objective of this testing was to determine if service aging in the durability facility was affecting the DMA curves. Changes in polymer structure are reflected by changes in the DMA curves. Dynamic mechanical analysis has been used by many researchers to evaluate the effects of aging, solvent attack, and UV degradation of polymers.

3.3.2 Specimen Configuration

Specimens were cut from the bulk windshield material away from the edges. The specimens were rectangular beams, 2.5 inch x 0.5 inch x 0.1 inch nominal. One specimen was fabricated from each of the two polycarbonate plies and from the acrylic ply from each windshield.

3.3.3 Test Method

Each ply was analyzed in flexure from -125° to 175°C using a 2°C/min heating rate at a fixed frequency of 1.0 Hz using a Dupont Dynamic Mechanical Analyzer.

3.3.4 Test Data

DMA scans of the transparency specimens are shown in Figures 3.6-3.9. Table 3.3 summarizes the glass transition temperatures (Tg) for each specimen which were determined from the maximum of the loss modulus curve, E".

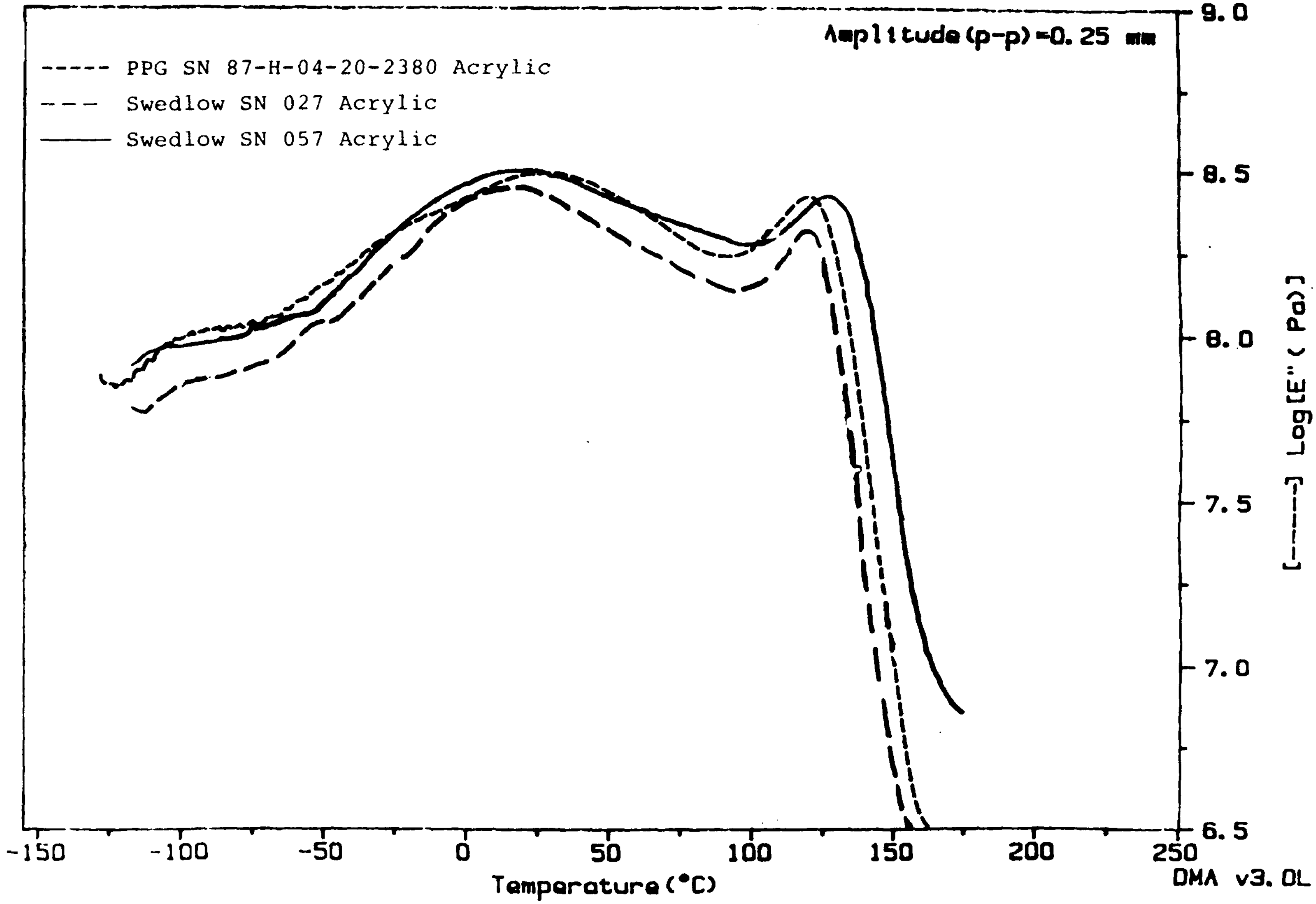


Figure 3.6. DMA Scan of Acrylic Surface Plies.

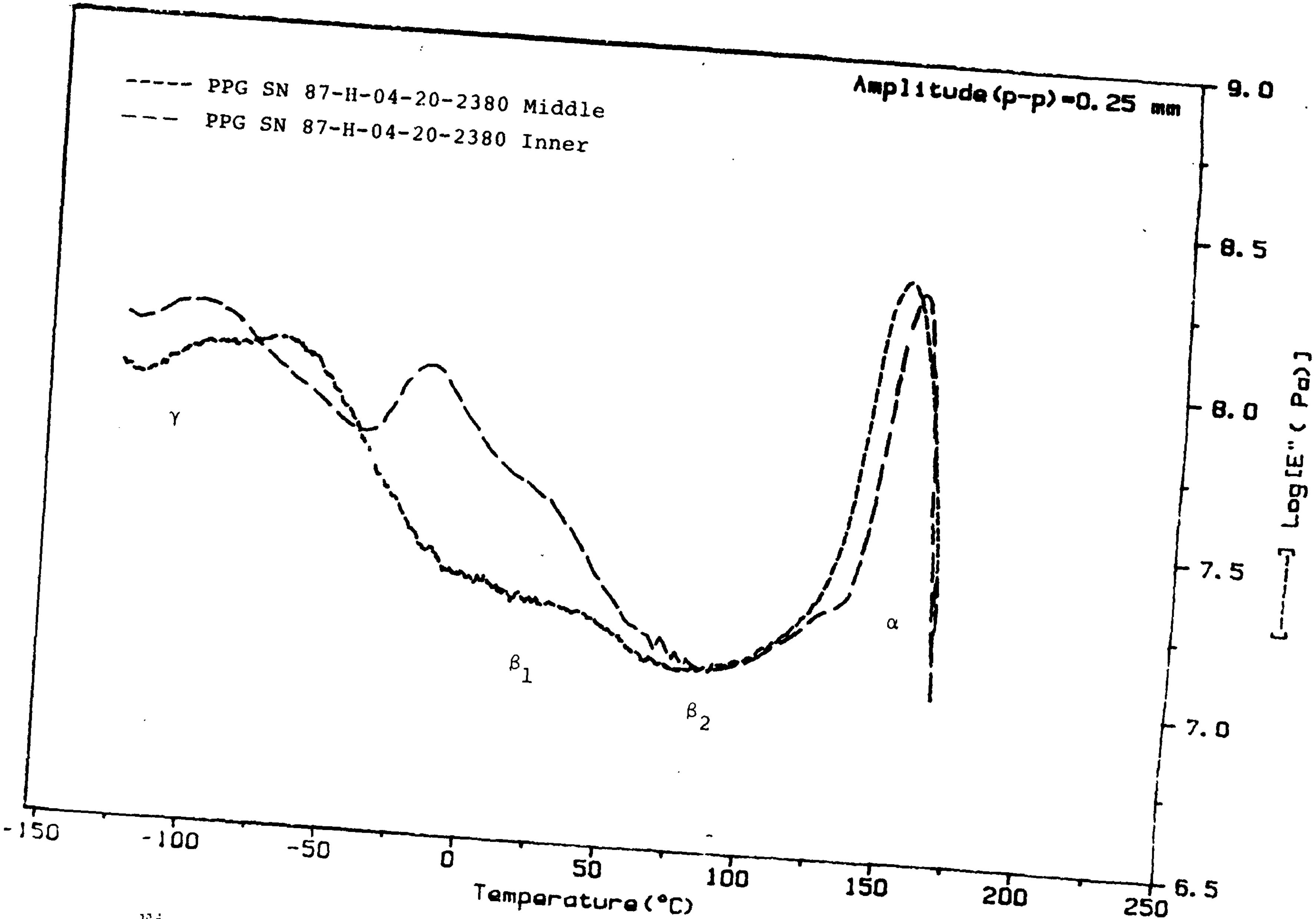


Figure 3.7. DMA Scan of PPG SN-H-04-20-2380 Polycarbonate Plies.

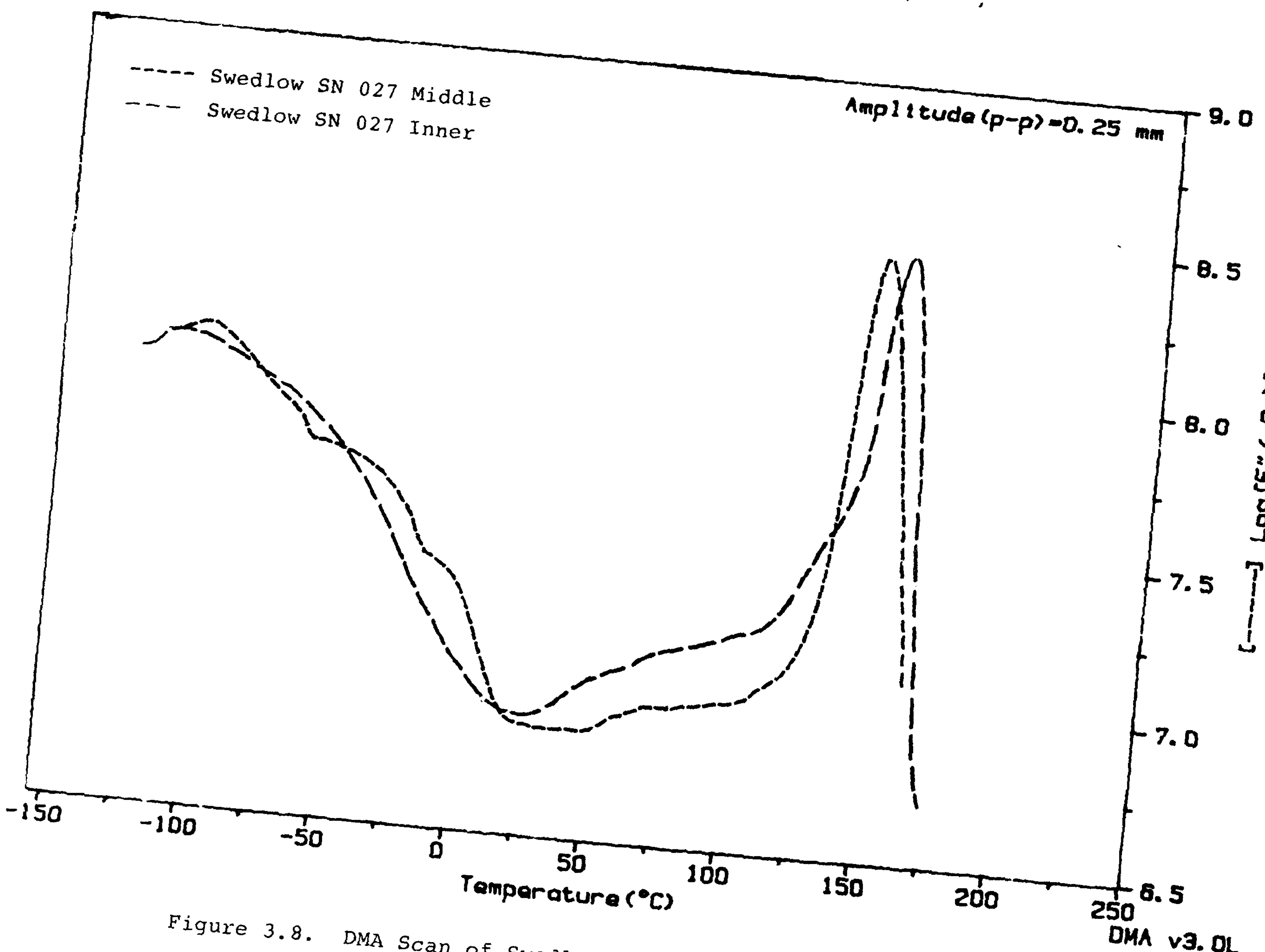


Figure 3.8. DMA Scan of Swedlow SN 027 Polycarbonate Plies.

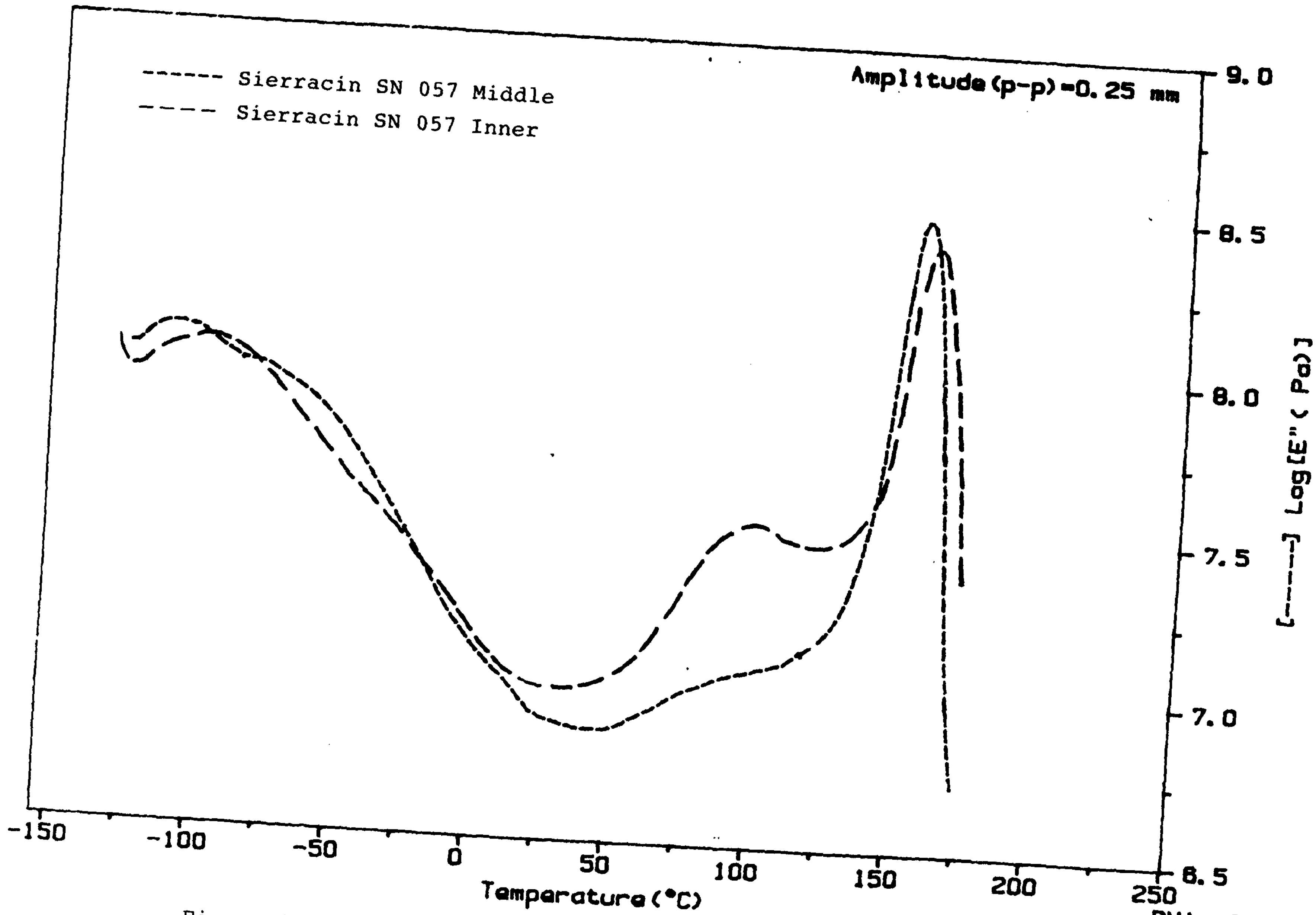


Figure 3.9. DMA Scan of Sierracin SN 057 Polycarbonate Plies.

TABLE 3.3

GLASS TRANSITION TEMPERATURES FROM DMA

MANUFACTURER/ SERIAL NUMBER	PLY	Tg (°C)
PPG SN 87-H-04-20-2380	Acrylic	119
	Middle Polycarbonate	150
	Inner Polycarbonate	155
Swedlow SN 027	Acrylic	118
	Middle Polycarbonate	147
	Inner Polycarbonate	156.5
Sierracin SN 057	Acrylic	126
	Middle Polycarbonate	156
	Inner Polycarbonate	160

3.3.5 Data Analysis/Correlation

Nomenclature used in this report to describe transitions and relaxations in Dynamic Mechanical Analysis of polycarbonate are as follows: α=Tg (glass transition temperature) $\approx$ 150°C, $\beta_1 \approx$ 25°C, $\beta_2 \approx$ 80°C, and $\gamma \approx$ -100°C, as used in Reference 2. The α, β_1, β_2, and γ general regions are shown in Figure 3.7.

There is evidence of physical aging/thermal history (annealing effects) in the -35 to 135 temperature range; however, these changes do not appear to be significantly affecting the polycarbonate mechanical properties as evidenced by the tensile testing. There are no major changes in the shape or location of the loss peak which is associated with the glass transition temperature (the so called alpha transition) and this is evidence that there is no significant chain scission or cross-linking taking place, and therefore no changes in molecular weight would be expected. Large changes in molecular weight would be evidenced by significant locational changes of the loss peak. For all manufacturers, the alpha transition occurs at a temperature of 5°C to 10°C lower for the middle (outboard) polycarbonate ply than for the inner polycarbonate ply. Except for the PPG specimens, the gamma peak is also fairly stable in shape and location. The beta two peak is recognizable for the Swedlow and Sierracin specimens; however, it is very subtle and difficult to recognize for the PPG specimens. In all cases, the height of the beta two peak is smaller for the middle (outboard) polycarbonate ply (the height of the beta two peak has been reported to decrease as a specimen experiences thermal aging). This is consistent with the actual thermal environment experienced by the windshield. The middle (outboard) polycarbonate ply experiences more time at higher temperatures in the Durability Facility. The cockpit interior is maintained at a nominal temperature of 75°F and the inner (inboard) polycarbonate ply stays relatively cool. In actual field conditions, however, the inboard polycarbonate ply does experience significant elevated temperatures on the flight line. Cockpit temperatures have been reported to be as high as 200°F in the summertime. The Durability Facility does not currently simulate this flightline condition. There was no significant difference between inboard and outboard polycarbonate ply dynamic mechanical analysis plots from the testing of baseline and in-service aged F-111 windshields as reported in Reference 2. This would indicate that both plies are experiencing similar thermal aging in the field. The thermal aging detected here and in the Reference 2 program is not significantly affecting polycarbonate mechanical properties.

With time thermal aging would be expected to cause degradation of the mechanical properties. The results of the Reference 2 program indicated no significant bulk polycarbonate degradation with up to 5 years of in-service aging.

3.4 GEL PERMEATION CHROMATOGRAPHY (GPC) TESTS

3.4.1 Test Objective

The objective of the GPC testing was to determine if service aging in the durability facility produced a molecular weight reduction of the polycarbonate.

3.4.2 Specimen Configuration

Shavings of polycarbonate were removed from the center of the individual plies. They were dissolved in tetrahydrofuran (THF). Many of the samples were difficult or impossible to completely dissolve even after a week in the solvent and several hours in an ultrasonic bath. The undissolved residue was assumed to be additives.

3.4.3 Test Method

GPC measurements were conducted utilizing an HP 1090A liquid chromatagraph GPC system. Polystyrene standards were used and the column used was a Phenomenex Ultracarb 5 micron particle size linear column, 30 cm long, mixed porosity for covering the greatest range of molecular weights, approximately 400 to 1,000,000. Polycarbonate molecular weight calibration tables were used to obtain molecular weights.

3.4.4 Test Data

A summary of the test data is presented in Table 3.4 and Figures 3.10-3.13 are plots of molecular weight distribution.

3.4.5 Data Analysis/Correlation

The PPG specimens had higher molecular weights than those from Swedlow or Sierracin. This in itself is not any indication of degradation, because the companies do not all use the same supplier of polycarbonate. The middle (outboard) polycarbonate ply for Sierracin and Swedlow had a slightly lower molecular weight than the inner (inboard) polycarbonate ply. This may be an indication of thermally induced molecular weight degradation. The middle (outboard) polycarbonate ply experiences greater temperatures than the inboard ply. However, the results of the tensile testing indicate that this reduction is not causing a structural problem.

TABLE 3.4

GEL PERMEATION CHROMATOGRAPHY RESULTS

MANUFACTURER/ SERIAL NUMBER	PLY	M_n	M_W	M_Z
PPG SN 87-H-04-20-2380	Middle Polycarbonate	10890	31100	57860
	Inner Polycarbonate	10980	30180	55250
SWEDLOW SN 027	Middle Polycarbonate	7744	23190	46730
	Inner Polycarbonate	7160	23670	48280
SIERRACIN SN 057	Middle Polycarbonate	6810	21330	44300
	Inner Polycarbonate	7254	22870	47460

NOTES:

M_N = number average molecular weight
M_W = weight average molecular weight
M_Z = Z average molecular weight

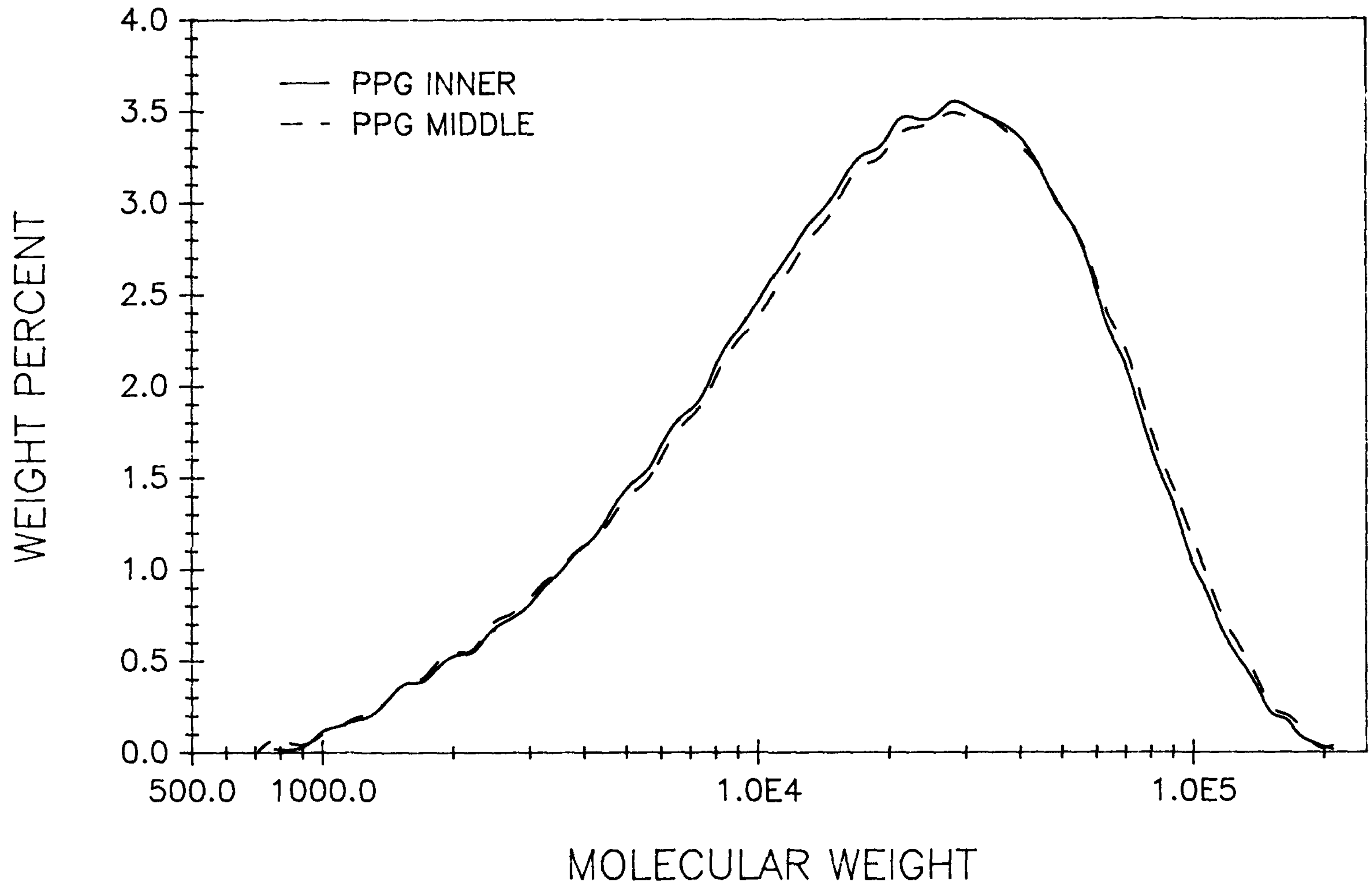


Figure 3.10. Polycarbonate Molecular Weight Distribution from PPG Windshield, SN 87-H-04-20-2380.

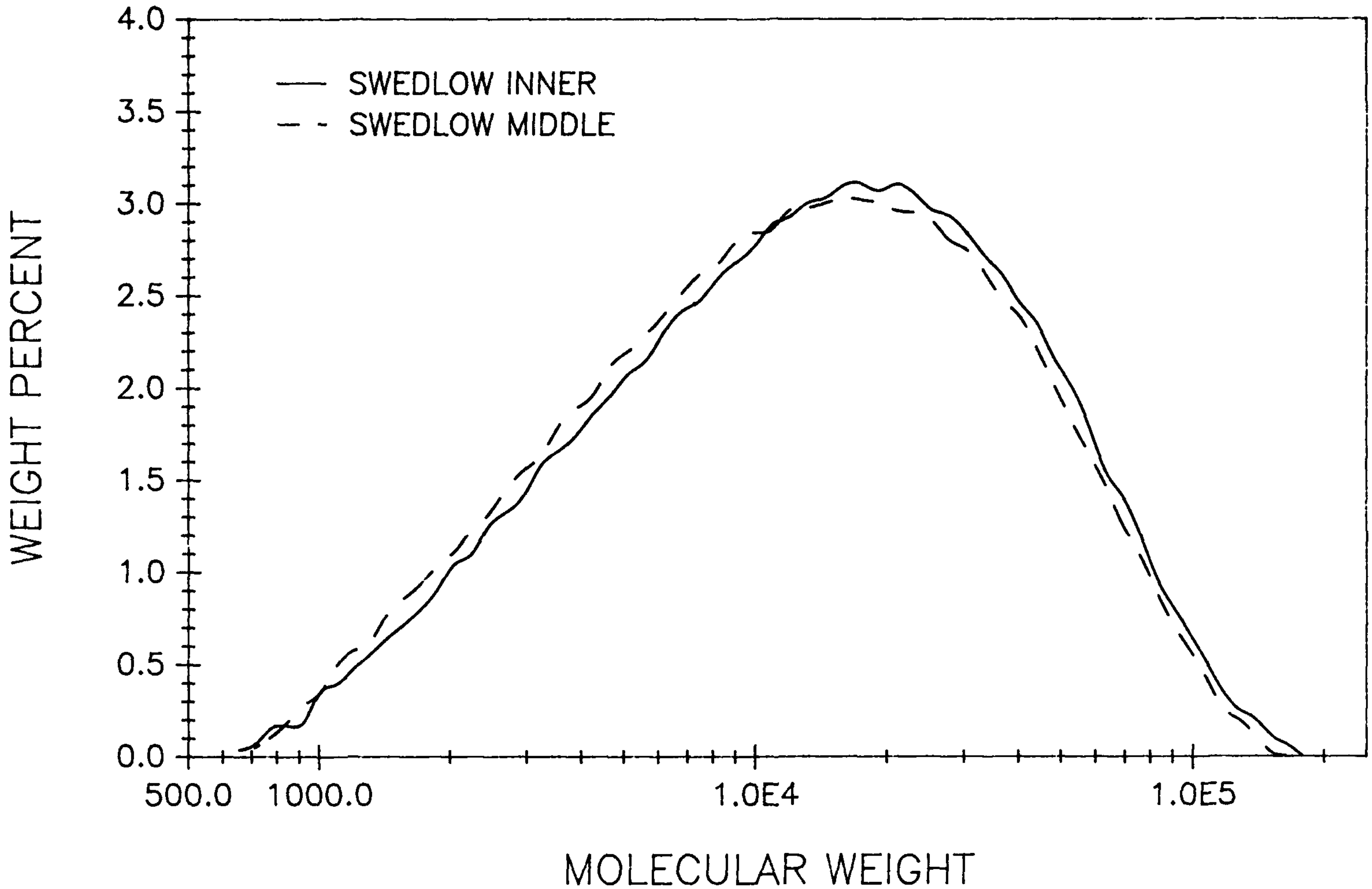


Figure 3.11. Polycarbonate Molecular Weight Distribution from Swedlow Windshield, SN 027.

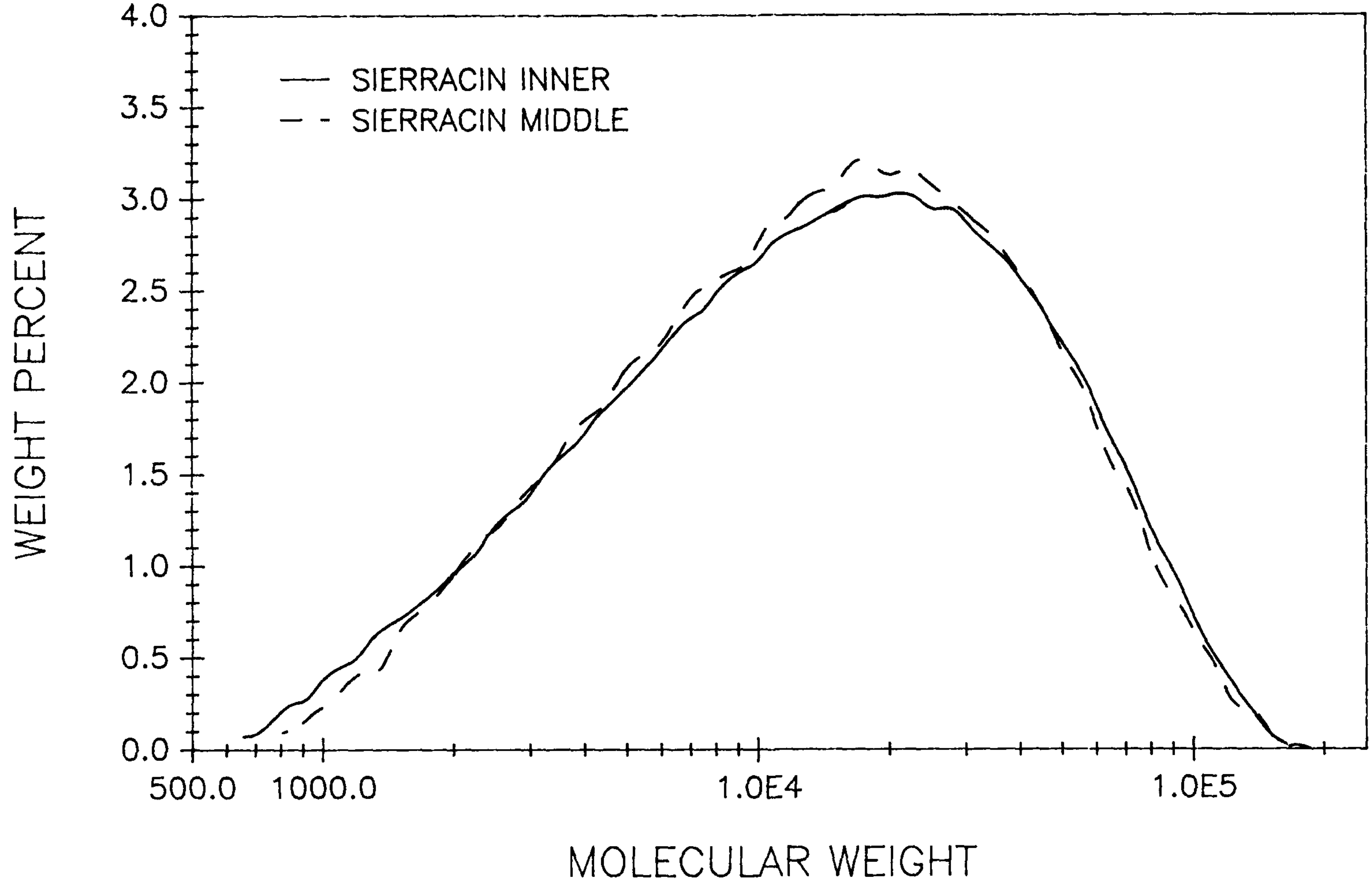


Figure 3.12. Polycarbonate Molecular Weight Distribution from Sierracin Windshield, SN 057.

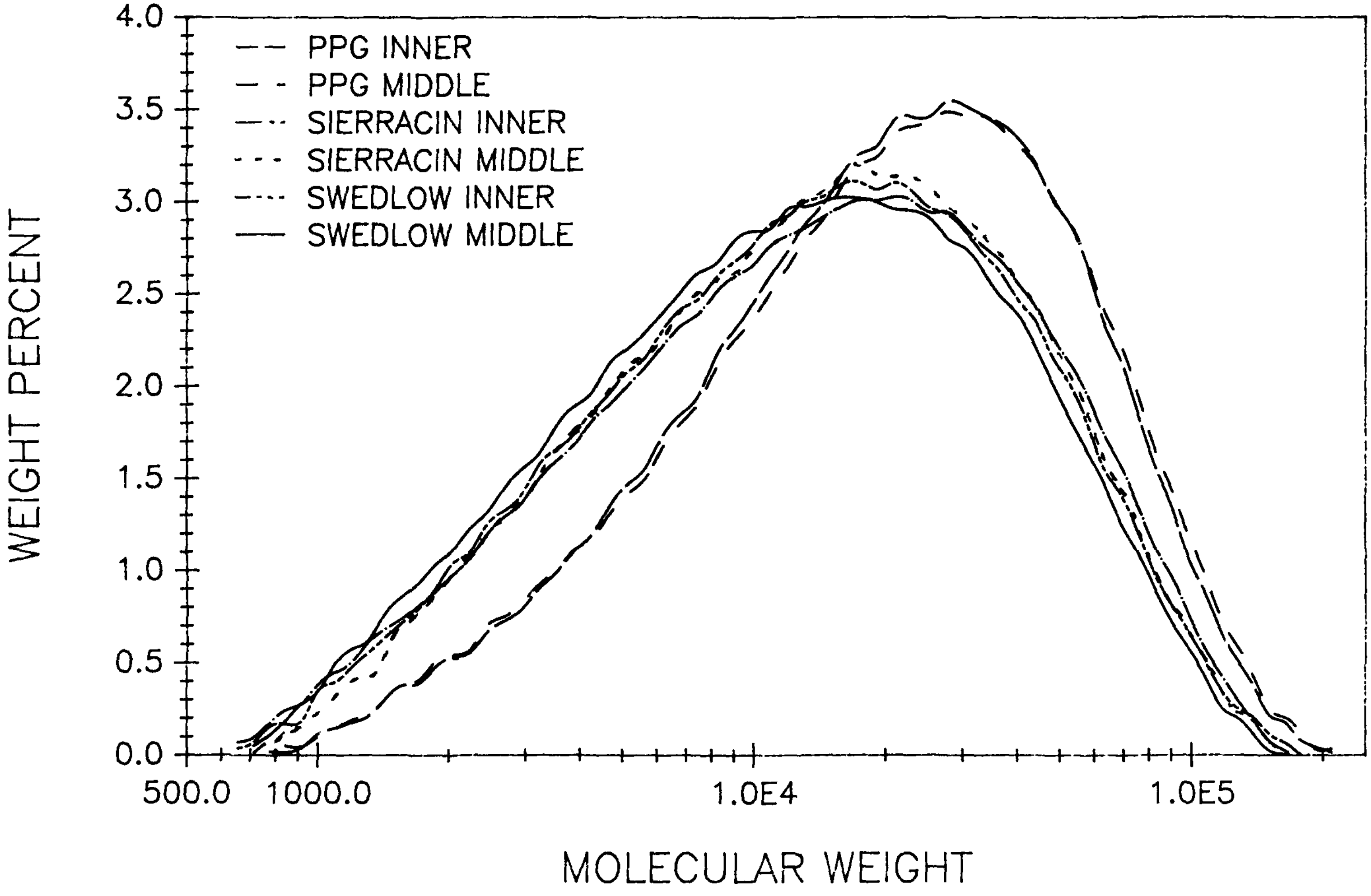


Figure 3.13. Polycarbonate Composite Molecular Weight Distribution from PPG, Swedlow, and Sierracin Windshields.

The number average (M_n) and weight average (M_w) molecular weights for Sierracin and Swedlow from this program were lower than the corresponding molecular weights for Sierracin and PPG specimens from the Reference 2 program. This may indicate that the thermal profiles used at the durability facility are more severe than those experienced in service. Additional testing would be required to confirm this.

Overall, there is no evidence of significant molecular weight reduction for the specimens tested, which included the bulk polycarbonate. It is possible that there is molecular weight reduction in the top 5-10 microns of the surfaces at the transparency edges and/or at the bolt holes which is not detected by the testing.

SECTION 4
CRACK ANALYSIS

Prior to birdstrike testing and coupon testing, the sealant at the windshield edges was removed to determine if cracks existed at the edges and in the vicinity of the bolt holes. Similar studies conducted by UDRI in the Reference 2 program revealed numerous fatigue cracks in windshields which had been removed from service. The results of this crack study are shown below.

MANUFACTURER/ SERIAL NO.	WINDSHIELD	SIMULATED SERVICE LIFE	POLY. CRACKS INBOARD/OUTBOARD
PPG SN 87-H-04-20-2380	Left	6.25 mo.	no visible cracks
PPG SN 86-H-11-04-2010	Right	6.25 mo.	74/68
Swedlow SN 027	Left	2 y. 9.9 mo.	3/2
Swedlow SN 018	Right	2 y. 9.9 mo.	none/4
Sierracin SN 057	Left	4 y. 1 mo.	none/56
Sierracin SN 082	Right	4 y. 1 mo.	none/6

Analysis of the crack documentation was completed to determine patterns in crack location (sill, center beam, aft arch, forward arch, inboard polycarbonate ply, outboard polycarbonate ply), direction of travel, and length. Only one of the transparencies (PPG SN 87-H-04-20-2380) was crack free. However, observation of the failure surfaces from the tensile edge attachment testing, reported in Section 3.1, revealed pre-existing fatigue cracks in PPG SN 87-H-04-20-2380 at two bolt holes (six specimens were tested with two bolt holes per specimen). These cracks were not detected by eye during the crack study reported in this section. It is likely that a number of fatigue cracks exist in each of the windshields which were not detectable by eye. In contrast, the companion right hand windshield (PPG SN 86-H-11-04-2010) had 142 cracks. If it can be assumed that both windshields experienced the same exact test history (and there is no reason to believe that they did not), it is possible that an inconsistency in manufacturing caused these differences in cracking. The same comment can be made for the two Sierracin windshields; however, the disparity between crack numbers is not as great, and the Sierracin windshields had much greater simulated service life.

We did not see any correlation between simulated flight hours and total number of cracks. The crack analysis conducted in the Reference 2 program indicated a correlation between total number of cracks and in-service age with a general trend of increasing crack length and number with increasing service life. A possible explanation for this disparity between cracks produced by simulated life and actual service life is that the temperature cycling that occurs on the flight line (hot summer days and cold winter nights) may produce relatively uniform crack growth, while the in-flight pressure/thermal loading conditions, which are of shorter duration and are more random, may produce random growth. Also, crack initiation is a somewhat random event and this effort represents only a limited number of data points. Another difference between simulated service life and in-service aged windshield cracking is crack location by ply. In the Reference 2 program, the majority (on the order of 90%) of the cracks occurred in the inboard ply, while for the windshields with simulated service life, the outboard polycarbonate ply tended to have more cracks. This may also be attributed to thermal conditions not simulated at the Durability Facility, or to saturation of the edges of the windshields during windshield and overall aircraft cleaning in the field. The inboard ply would be exposed to solutions that collect at the edges between the windshield and the frame more so than the outboard ply, and would be more susceptible to chemical crazing followed by crack growth for windshields in the field. The Durability Facility installs the windshields according to the F-111 T.O., which requires cleaning of the frame with isopropyl alcohol prior to sealing, application of a primer (EC1945B) to the frame, and then sealing with Pro-Seal 899B-2. Both the primer and the sealant have been found to cause crazing of polycarbonate. Very few cracks initiated at the transparency edges for the windshields from the Durability Facility; most cracks initiated at the bolt holes (except for Sierracin SN 057 which had extensive crazing/cracking along the edges). The windshields from the Reference 2 program had roughly equivalent numbers of cracks at the bolt holes and the edges for Sierracin windshields, while there were many more cracks at the edges for PPG windshields.

SECTION 5

FULL-SCALE BIRDSTRIKE TESTING

5.1 TEST SETUP AND TEST FACILITY

The birdstrike testing was conducted at the University of Dayton Impact Physics Range 5, see Figure 5.1. An F-111E crew escape module, Air Force serial number 68-024, was used as a test stand. The center beam and the windshield aft arch were fabricated using high strength steel as designed by UDRI to simulate the dynamic structural behavior of the actual system. The UDRI simulated arch/center beam assembly is shown in Figure 5.2, and a comparison of cross-section properties for the UDRI test hardware and flight hardware is shown in Figure 5.3. A more complete description of the development of this test hardware is documented in Reference 1. Three right hand aft arches were manufactured for this effort to allow for expected structural damage. A new arch was used for each of the three birdstrike tests.

Artificial 4-pound gelatin birds were impacted at the most critical location of the windshield, the upper inboard corner (see Figure 5.4). Right hand windshields were tested with the left hand windshield, canopy framework, and canopy transparencies installed. Three high-speed movie cameras (5000 frames/sec) were utilized to record each bird impact event. Camera locations are shown in Figure 5.5.

5.2 BIRDSTRIKE TEST RESULTS

The technical data from each of the birdstrike tests are summarized in the following standard data forms, and still photographs of each tested windshield are shown in Figures 5.6-5.8.

The Sierracin windshield had 122 mulated flight hours in the WRDC Building 68 ful!-scale durabili y facility, which is equivalent to approximately 4 years and 1 month of in-service aging. It was birdstrike tested at 373 knots and passed. The Swedlow windshield had 847 simulated flight hours, which is equivalent to approximately 2 years 10 months of in-service aging. It was birdstrike tested at 405 knots and passed. The PPG windshield had 156 simulated flight hours, which is equivalent to approximately 6 months of in-service aging. It was birdstrike tested at 475 knots and failed catastrophically. These test points are plotted

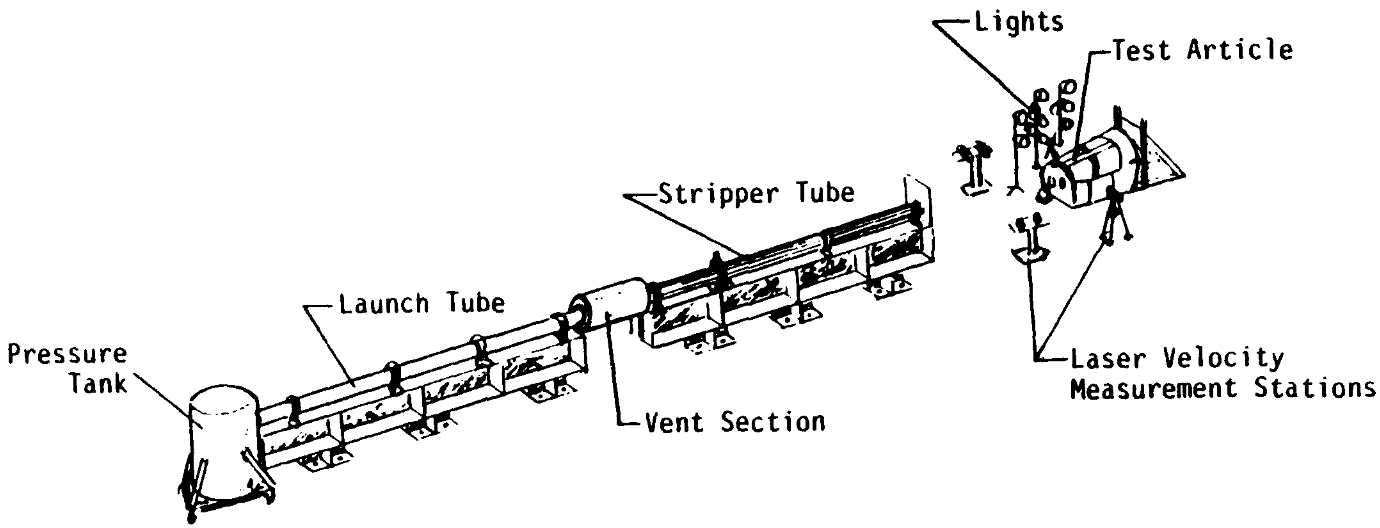


Figure 5.1. UDRI Impact Physics Test Range 5.

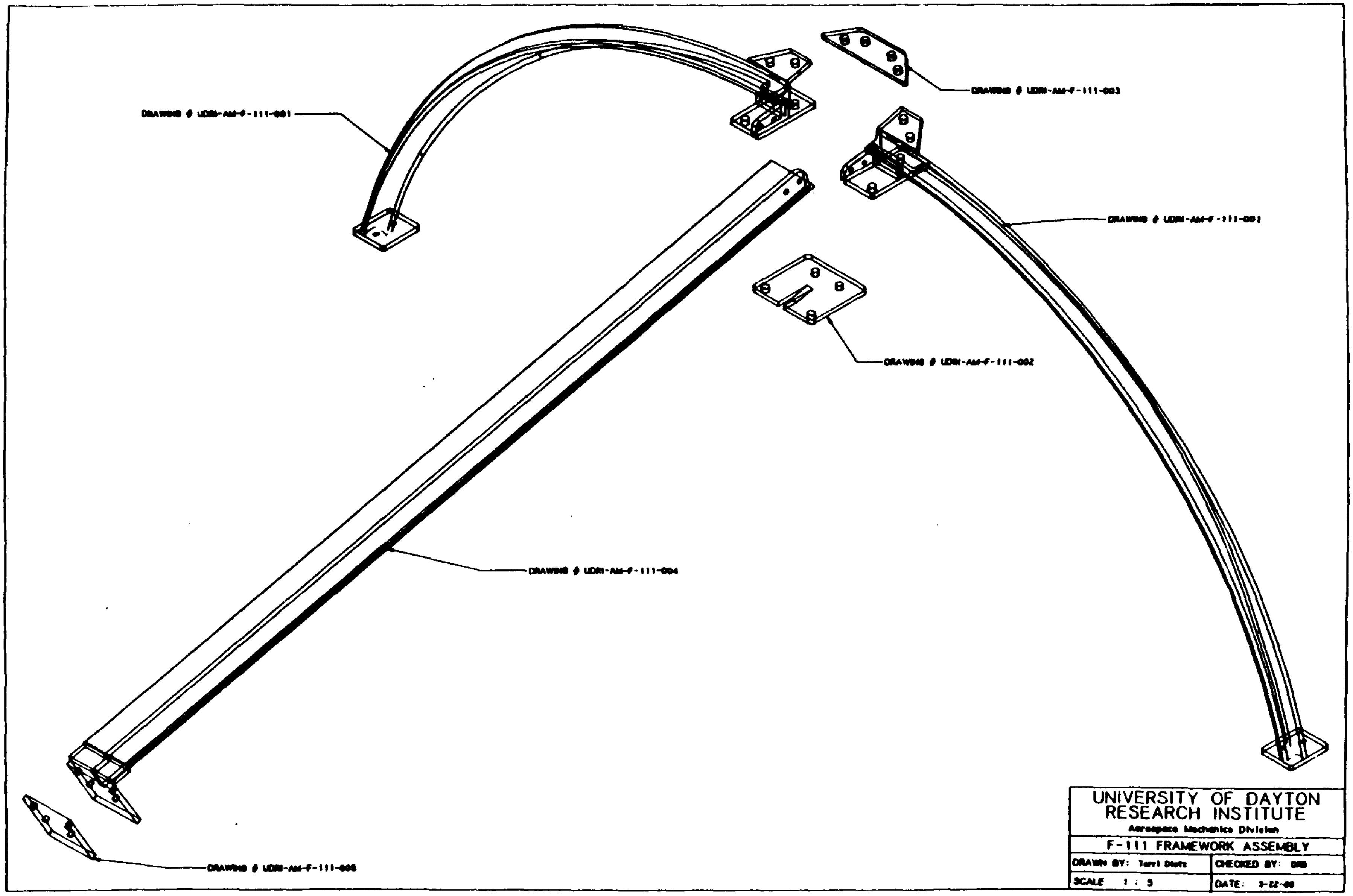
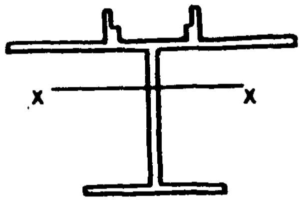


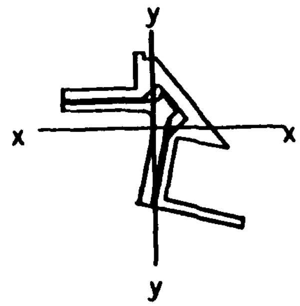
Figure 5.2. Aft Arch/Center Beam Assembly.

FLIGHT HARDWARE

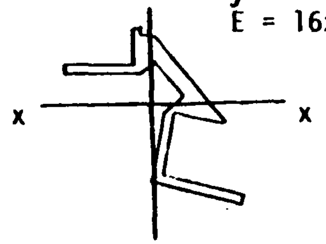
Material: Ti: 6Al-4v
$\sigma_u \approx 157$ ksi
$\sigma_y \approx 143$ ksi
$E = 16\times10^6$ psi



Existing Center Beam Properties
$I_{xx} = 0.294$ in.^{4} $I_{yy} = 0.267$ in.^{4}
$EI_{xx} = 4.70\times10^6$ lb.in.^{2} $EI_{yy} = 4.27\times10^6$ lb.in.^{2}



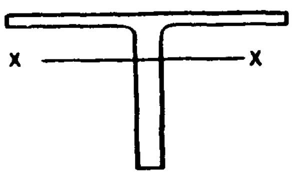
Existing Aft Arch Properties
Behind the Impact Point
$I_{xx} = 0.280$ in.^{4} $I_{yy} = 0.298$ in.^{4}
$EI_{xx} = 4.48\times10^6$ lb.in.^{2} $EI_{yy} = 4.77\times10^6$ lb.in.^{2}



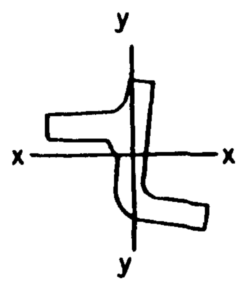
Existing Aft Arch Properties
6" Above the Sill
$I_{xx} = 0.158$ in.^{4} $I_{yy} = 0.091$ in.^{4}
$EI_{xx} = 2.53\times10^6$ lb.in.^{2} $EI_{yy} = 1.45\times10^6$ lb.in.^{2}

TEST HARDWARE

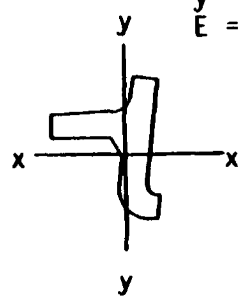
Material: AISI-4130
$\sigma_u \approx 163$ ksi
$\sigma_y \approx 145$ ksi
$E = 29\times10^6$ psi



UDRI Center Beam Properties
$I_{xx} = 0.204$ in.^{4} $I_{yy} = 0.30$ in.^{4}
$EI_{xx} = 5.92\times10^6$ lb.in.^{2} $EI_{yy} = 8.72\times10^6$ lb.in.^{2}



UDRI Aft Arch Properties
Behind the Impact Point
$I_{xx} = 0.154$ in.^{4} $I_{yy} = 0.105$ in.^{4}
$EI_{xx} = 4.46\times10^6$ lb.in.^{2} $EI_{yy} = 3.05\times10^6$ lb.in.^{2}



UDRI Aft Arch Properties
From Sill to 6" Above the Sill
$I_{xx} = 0.078$ in.^{4} $I_{yy} = 0.049$ in.^{4}
$EI_{xx} = 2.26\times10^6$ lb.in.^{2} $EI_{yy} = 1.43\times10^6$ lb.in.^{2}

Figure 5.3. Comparison of Cross-Section Properties Between Flight Hardware and UDRI Test Hardware.

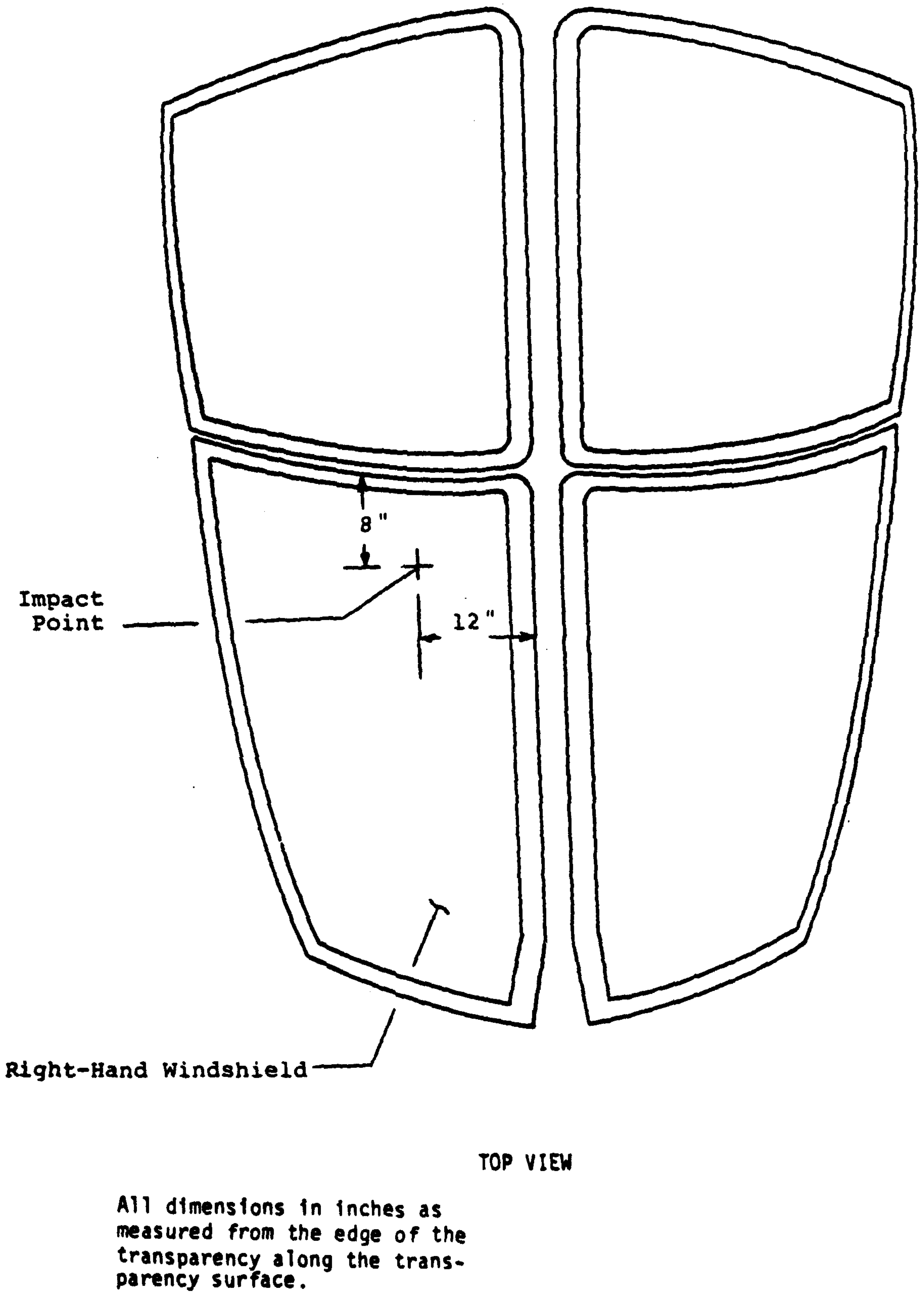


Figure 5.4. Bird Impact Location.

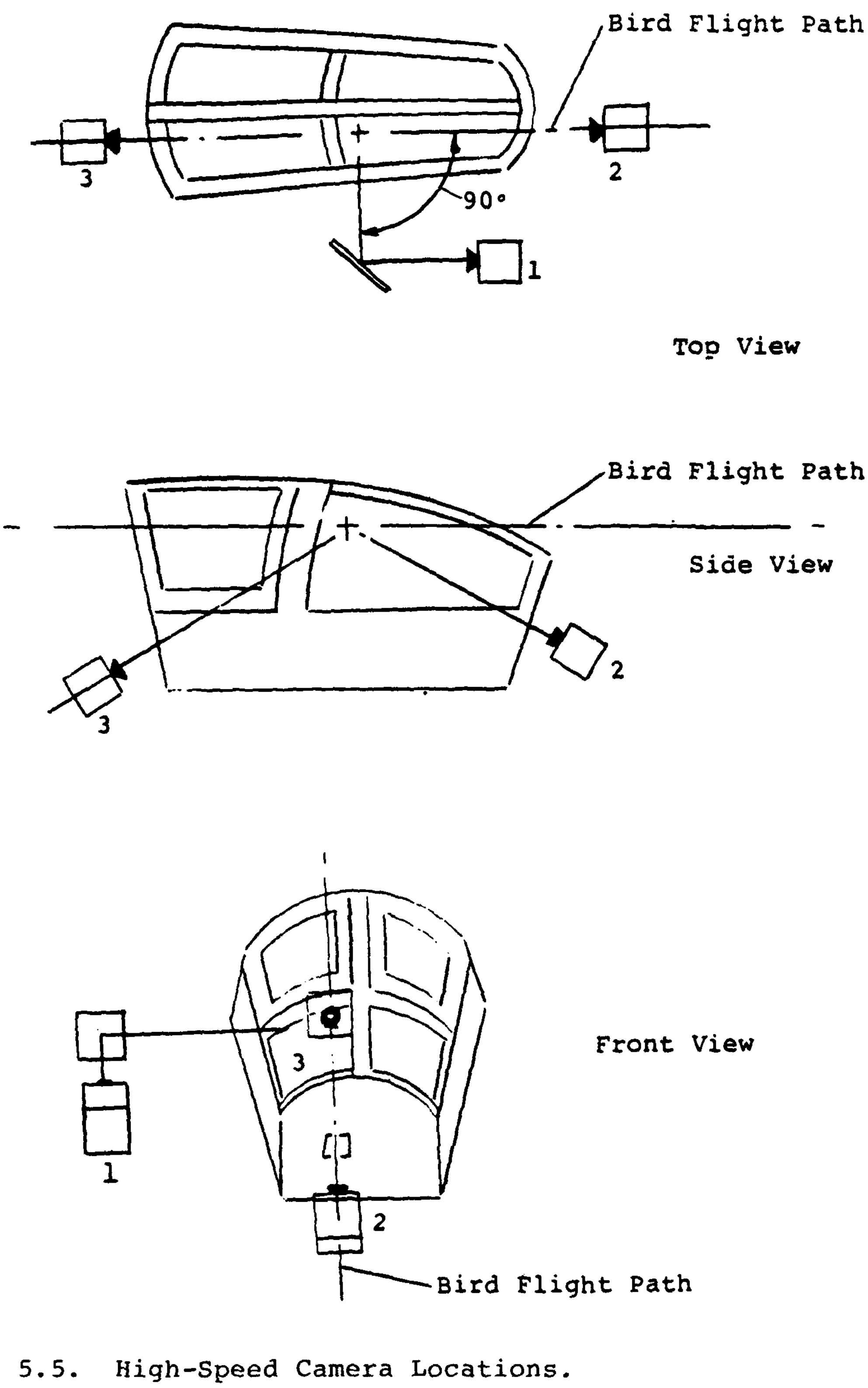


Figure 5.5. High-Speed Camera Locations.

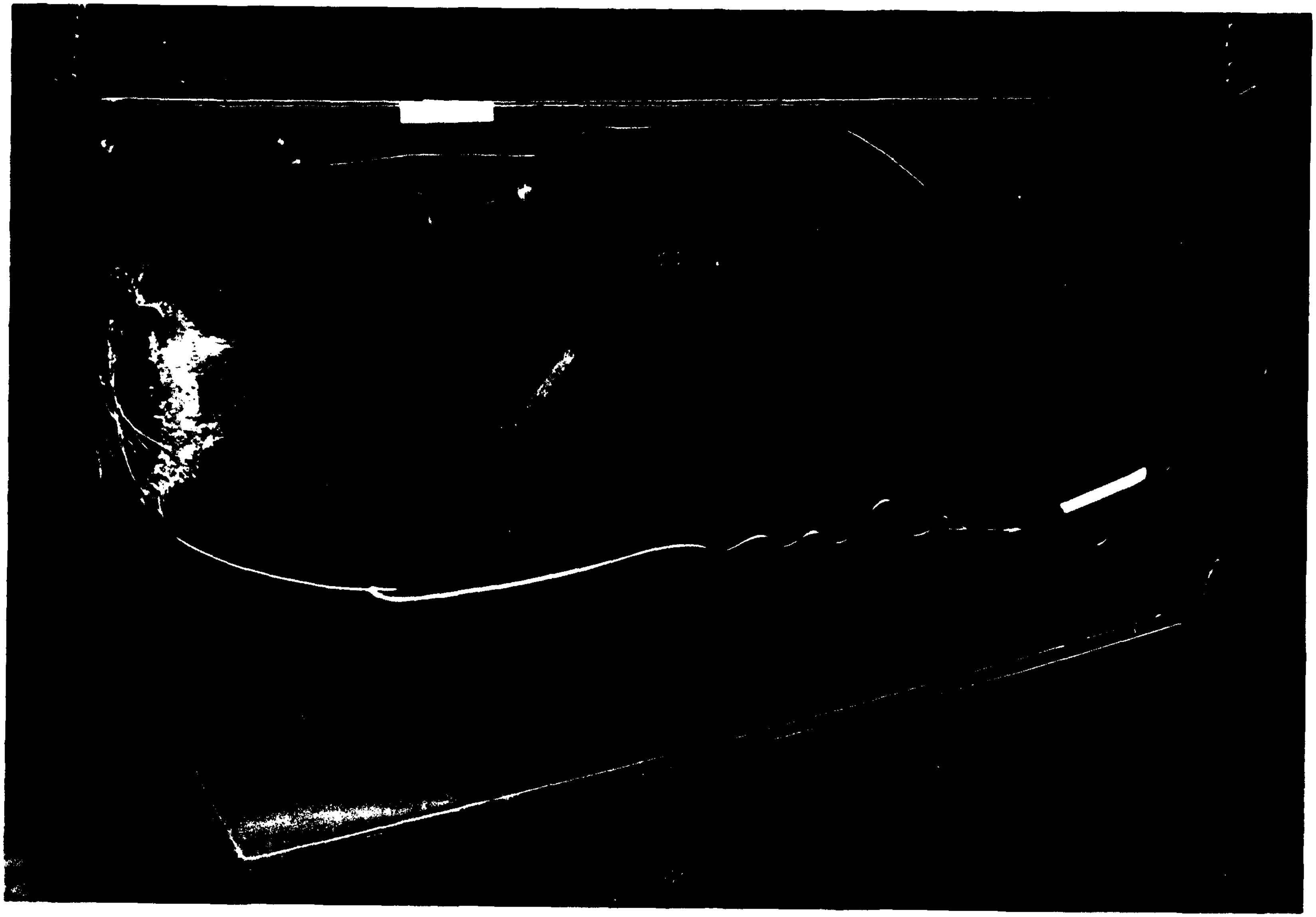


Figure 5.6. Birdstrike Tested F-111 ADBIRT Windshield, Sierracin SN 082.

UDRI
F-111 RIGHT-HAND TRANSPARENCY
BIRD IMPACT TEST

TEST SUMMARY

I. BASIC TEST DATA

Date of Test: 9/11/90 Test No.: 5-0620
Impact Pt.: 8" down from aft edge, 12" over from center beam (standard) impact point
Planned Impact Vel.: 365 kts (617 fps) Actual Impact Vel.: 373 kts (631 fps)
Bird Wt.: 4.055 Ambient Temperature: 71°F

II. TEST HARDWARE

Crew Module Ident. AFSN 68-024 MFGR. SN 227

R/H Windshield:
Manufacturer: Sierracin
Serial Number: SN 082
Date of Manufacture: 8-84
Test History: 1225 simulated flight hours
Weight: 49.3#
L/H Windshield: PPG 015-057 DOM 9-23-80
R/H Canopy: PPG 504973 FSPP DOM 3-26-75
L/H Canopy: Sierracin SN 013 DOM 9-77

Aft Arch Configuration: UDRI simulated aft arch

Fasteners:	Screws	Nuts	Washers	Torque
Aft Arch:	NAS1203-17	MS 21043-3	#10 SAE	40 in-lb
Center Beam:	NAS1204-15	1/4# Grade B	1/4" SAE	25 in-lb
Sill:	NAS1204-15	1/4# Grade B	1/4" SAE	25 in-lb
Forward Arch:	NAS1203-17	10-32 Machine	#10 SAE	25 in-lb

III. PRE-TEST OBSERVATIONS

Some surface scratches, small delamination at forward corner by center beam. Distortion of acrylic at forward corner by the sill.

IV. POST-TEST OBSERVATIONS

Impact point dead on, surface acrylic cracking, evidence of ductility behind the the impact point. Small permanent pocket, very small permanent radial deformation of aft arch and forward flange rolled over slightly. Bolts behind impact point deformed.

V. SIGNIFICANCE OF TEST

Pass at 373 knots. Transparency is not degraded as bad as in-service aging would indicate. Transparency looks capable of withstanding higher velocity.

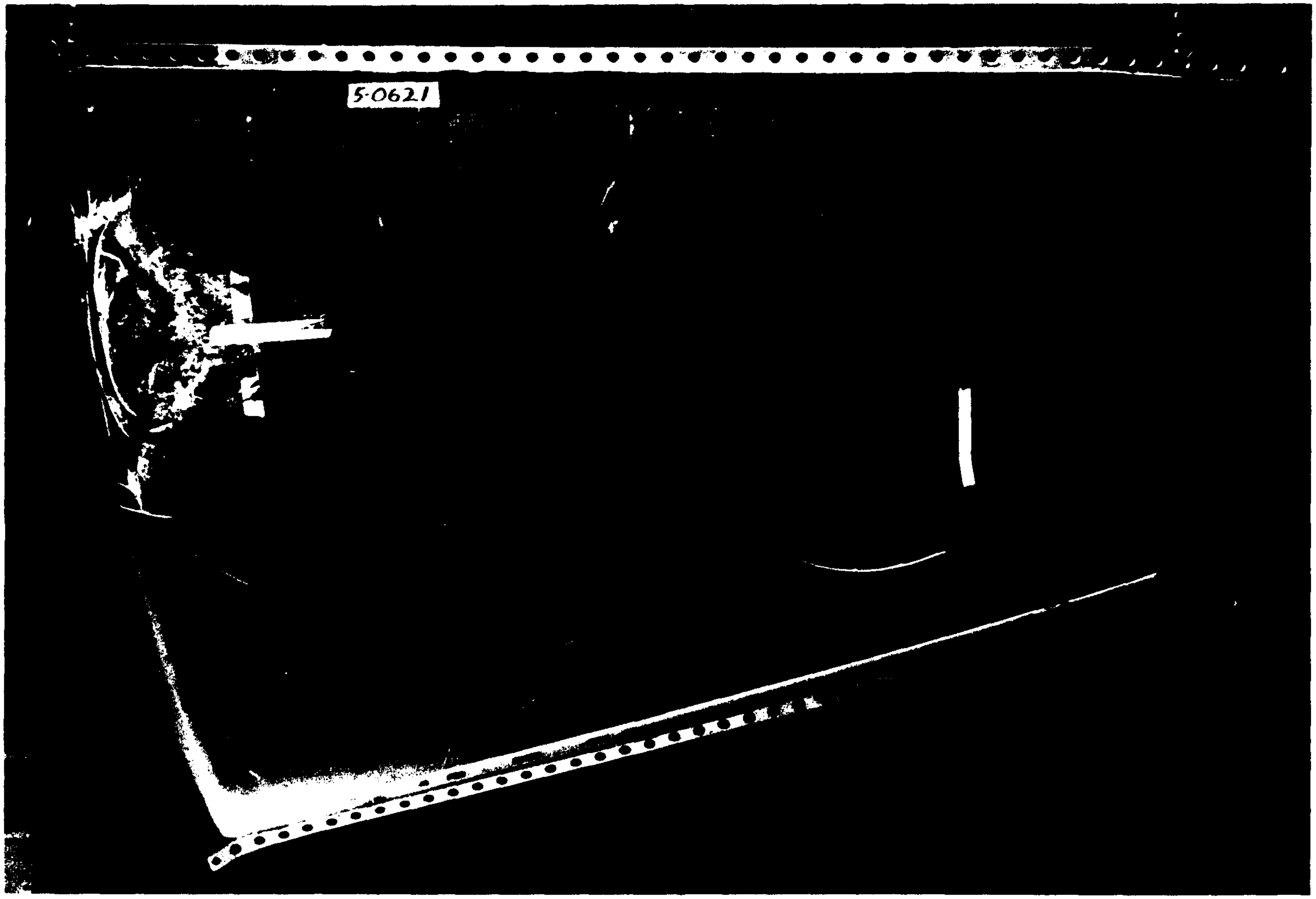


Figure 5.7. Birdstrike Tested F-111 ADBIRT Windshield, Swedlow 018.

UDRI
F-111 RIGHT-HAND TRANSPARENCY
BIRD IMPACT TEST

TEST SUMMARY

I. BASIC TEST DATA

Date of Test: 9/13/90 Test No.: 5-0621
Impact Pt.: standard

Planned Impact Vel.: 400 kts (676 fps) Actual Impact Vel.: 404.6 kts (683 fps)
Bird Wt.: 4.054 Ambient Temperature: 71°F

II. TEST HARDWARE

Crew Module Ident.

R/H Windshield:
Manufacturer: Swedlow (86175)
Serial Number: 018
Date of Manufacture: 8-86
Test History: 847 simulated flight hours
Weight: 48.5#
L/H Windshield: PPG 015-057 DOM 9-23-80
R/H Canopy: PPG 504973 FSPP DOM 3-26-75
L/H Canopy: Sierracin SN 013 DOM 9-77

Aft Arch Configuration: UDRI simulated aft arch

Fasteners:	Screws	Nuts	Washers	Torque
Aft Arch:	NAS1203-17	MS 21043-3	#10 SAE	40 in-lb
Center Beam:	NAS1204-15	1/4# Grade B	1/4" SAE	25 in-lb
Sill:	NAS1204-15	1/4# Grade B	1/4" SAE	25 in-lb
Forward Arch:	NAS1203-17	10-32 Machine	#10 SAE	25 in-lb

III. PRE-TEST OBSERVATIONS

Some scratches, outer retainer loose in places, sealant between acrylic and retainer separated in places. Some delamination, acrylic distorted (wavy along edges).

IV. POST-TEST OBSERVATIONS

Target dead on, surface acrylic and sublayer cracking. Permanent pocket formed behind impact point. Bolts bent behind impact point on aft arch, aft arch deformed radially, and windshield support flange rolled over at impact point.

V. SIGNIFICANCE OF TEST

Pass at 405 knots. Transparency appears to be capable of withstanding higher velocity.

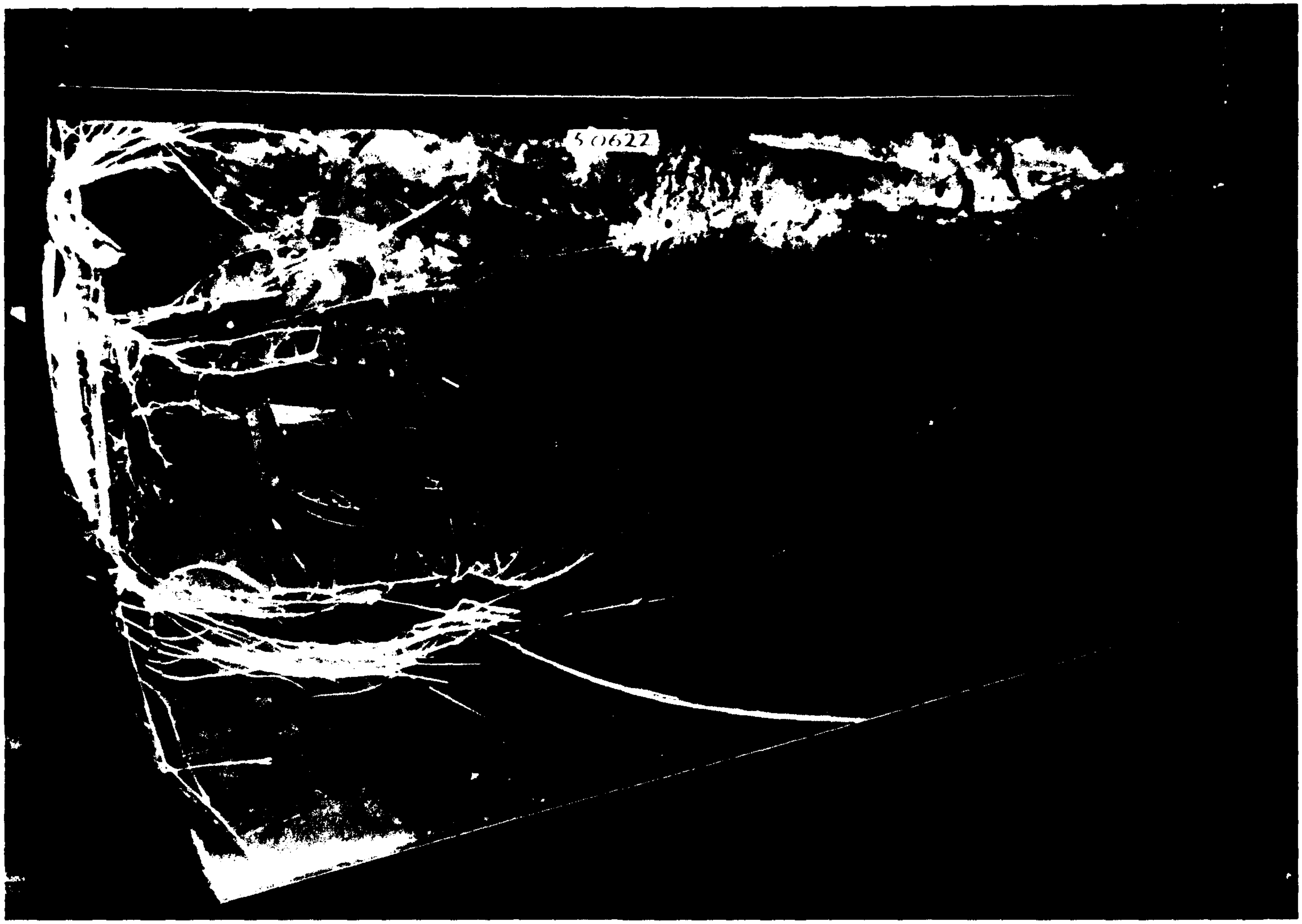


Figure 5.8. Birdstrike Tested F-111 ADBIRT Windshield, PPG SN 86-H-11-04-2010.

UDRI
F-111 RIGHT-HAND TRANSPARENCY
BIRD IMPACT TEST

TEST SUMMARY

I. BASIC TEST DATA

Date of Test: 9/14/90 Test No.: 5-0622
Impact Pt.: standard

Planned Impact Vel.: 460 kts (777.4 fps) Actual Impact Vel.: 475 kts (803 fps)
Bird Wt.: 4.046 Ambient Temperature: 71°F

II. TEST HARDWARE

Crew Module Ident.

R/H Windshield:
Manufacturer: PPG
Serial Number: LBSN 86-H-11-04-2010
Date of Manufacture: 11/86
Test History: 156 simulated flight hours
Weight: 48.3#
L/H Windshield: PPG 015-057 DOM 9-23-80
R/H Canopy: PPG 504973 FSPP DOM 3-26-75
L/H Canopy: Sierracin SN 013 DOM 9-77

Aft Arch Configuration: UDRI simulated aft arch

Fasteners:	Screws	Nuts	Washers	Torque
Aft Arch:	NAS1203-17	MS 21043-3	#10 SAE	40 in-lb
Center Beam:	NAS1204-15	1/4# Grade B	1/4" SAE	25 in-lb
Sill:	NAS1204-15	1/4# Grade B	1/4" SAE	25 in-lb
Forward Arch:	NAS1203-17	10-32 Machine	#10 SAE	25 in-lb

III. PRE-TEST OBSERVATIONS
Delamination around edges, also acrylic bubbled at edges. Large bubble at aft arch. Large bubble at sill. Interior coating somewhat milky and dirty.

IV. POST-TEST OBSERVATIONS
Extensive poly and acrylic cracking; large 15x15" piece of laminate broken out at impact point. Estensive delamination, 2 bolts sheared off. No apparent damage to arch.
Catastrophic failure.

V. SIGNIFICANCE OF TEST
Failure at 475 knots.

in Figure 5.9 on top of the test data from the birdstrike testing program conducted by UDRI of in-service aged F-111 windshields, Reference 1.

The Sierracin and Swedlow windshields passed birdstrike tests when shot at 50 knots above the capability curves which resulted from birdstrike testing of the in-service aged windshields. The PPG windshield failed at 45 knots above the capability curve (note there were a significant number of fatigue cracks in this windshield), however 475 knots is right at the limit of the capability for new windshields using the UDRI hardware. The full-scale durability facility currently simulates pressure/thermal profiles from the flight environment and cleaning operations, but does not include UV light, moisture, flightline cockpit heating, or ambient thermal effects (although several of these are being considered for incorporation into the facility). The differences in birdstrike degradation between simulated and actual service life are most likely a result of those environmental factors which are not simulated in the durability facility.

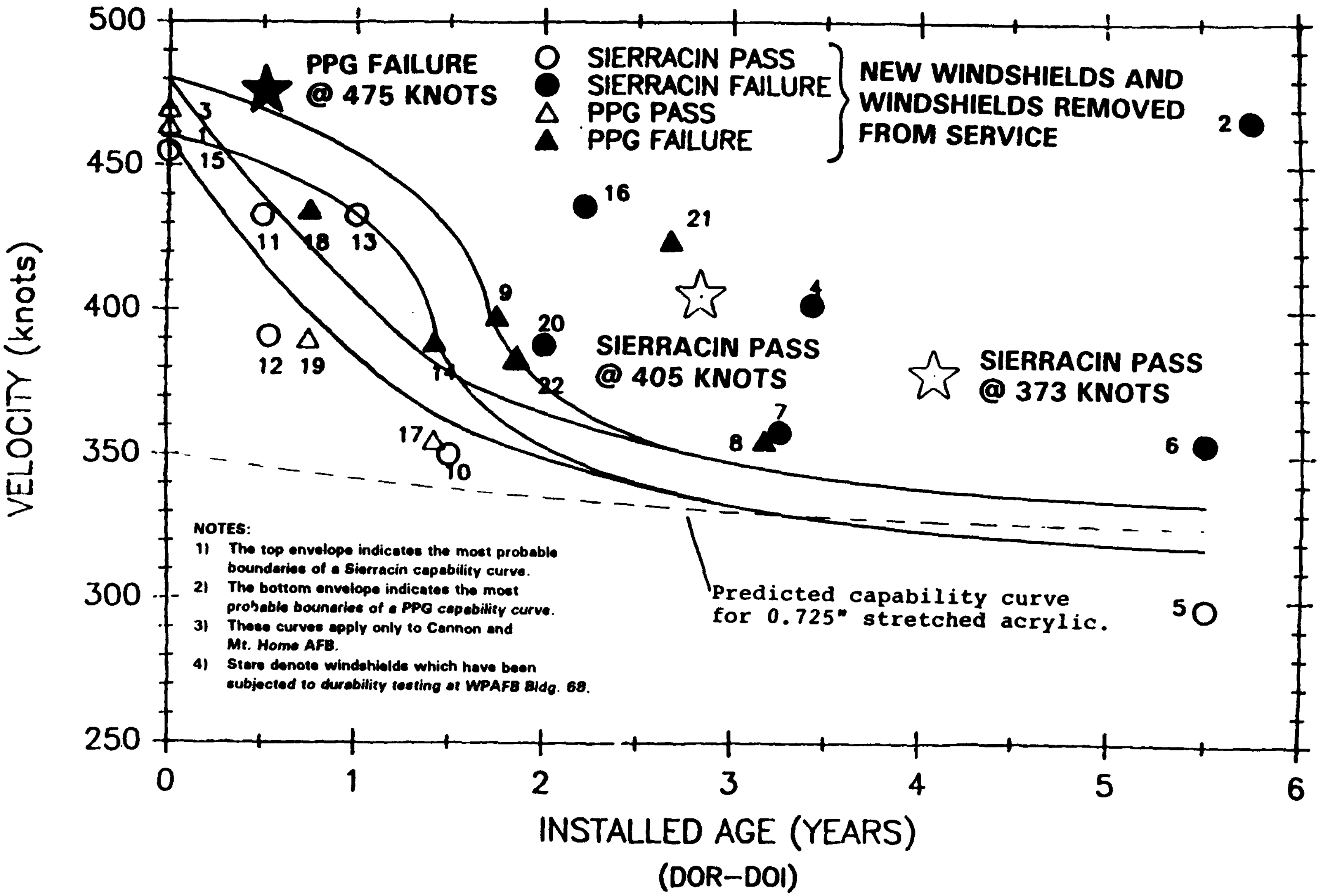


Figure 5.9. Birdstrike Test Results of New, Service Aged, and Durability Facility Aged F-111 ADBIRT Windshields.

SECTION 6

CONCLUSIONS/RECOMMENDATIONS

The objectives of this program were successfully accomplished, i.e., to determine if F-111 ADBIRT windshield transparencies subjected to simulated service life testing in the WPAFB Building 68 Durability Facility are experiencing structural degradation similar to in-service aged windshields, and to gain additional insight into the cause of edge-attachment cracking and subsequent structural degradation of in-service aged F-111 ADBIRT windshields.

Test results indicate that simulated service life in the WPAFB Building 68 Durability Facility is producing structural degradation, but this degradation is less severe in terms of birdstrike resistance than the structural degradation caused by actual in-service aging.

As concluded in the Reference 2 program, UV light is not a significant factor in the F-111 windshield structural degradation problem. The durability facility does not include UV light, and none of the resultant characteristics of UV degradation are present (e.g., molecular weight reduction, and embrittlement of the polycarbonate). There is evidence of thermal history/annealing; however, tensile testing shows that the bulk polycarbonate still retains an acceptable level of toughness. No evidence of chemical attack of the bulk polycarbonate was detected by gel permeation chromatography (GPC) or by dynamic mechanical analysis (DMA). Tensile edge attachment testing did not show any significant reduction in edge strength.

Craze research and testing from Reference 2 of sealants, cleaners, and other chemicals used for maintenance and installation of the F-111 transparency system indicated that chemical crazing is a likely initiator of fatigue cracks at the transparency edges. The pressure/thermal fatigue loadings on the F-111 windshield cause and/or extend cracks caused by other mechanisms. The fatigue crack tabulation and analysis brought to light the significance and magnitude of the crack problem. Although the cracking resulting from simulated service life was random, virtually none of the windshields studied were crack-free. Even though the entire in-service environment for the F-111 is not currently being simulated at the Durability Facility, cracks are still occurring. This cracking does not appear to be following the same trend as cracking produced by in-service aging. However, the cracking which occurs as a result of simulated service life in the Durability Facility does degrade birdstrike resistance.

Two additional windshields manufactured by PPG Industries that were not available to be tested in this program prior to the completion of the technical work have been tested in the Durability Facility. These were designed by PPG to overcome durability problems (associated with PPG windshields which were tested in this effort) and were installed with a non-aggressive dry seal. We recommend that these windshields be examined for edge cracking. This would allow determination of how much of an effect the wet seal and associated primer have on cracking. We suspect that cracking is present in those windshields as the pressure/thermal environment associated with the F-111 and the current edge design are sufficient alone to cause edge cracking. Other factors such as sealants, chemicals, moisture, etc., may decrease crack initiation time and accelerate crack growth speed.

Conclusions and recommendations of the Reference 2 program which are considered applicable to this effort are repeated as follows.

Craze testing of optical and machined surfaces has indicated that machined surfaces are more susceptible to craze than optical (polished, smooth) surfaces. A possible short-term solution, which would reduce the influence of moisture and chemical attack, and fatigue, would be to machine and polish the edges and the bolt holes to a very smooth finish (removing all sharp edges), and to use moisture and chemical resistant coatings on the interior and exterior windshield surfaces as well as interior surfaces of the bolt holes. Coatings could be used to effectively seal the entire transparency, thus greatly reducing or eliminating the effects of hydrolysis and/or chemical attack from cleaning solutions, etc. Also, the possibility of field contamination of those areas susceptible (which are the transparency edges and edge attachments) could be reduced by chemical craze testing all approved cleaning solvents, sealants, and other substances used, eliminating those substances which may directly attack the acrylic or attack the polycarbonate in the bolt holes or at the transparency edge. In addition, better education of field personnel on cleaning techniques may reduce chemical attack. The effects of flight loads and pressure/thermal loads could be reduced with new designs by using channel type edge attachments (fastenerless edge attachments similar to those used by other industries such as automotive/bus transparencies and architectural glass) or floating bushings. The aft edge attachment on the F-111 ADBIRT windshield is less than optimum because of the constraints imposed by the length of the forward flange on the existing titanium aft arch. In addition, the bird impact resistance of the existing windshield configuration could be improved with better edge attachment designs.

A long term solution for windshields such as the F-111, which have demanding mission profiles, would be to eliminate both chemical craze agents and holes for fasteners in the transparency. Elimination of the holes in the transparency would in turn eliminate the stress concentration points and the fatigue cracks. It is possible to develop a channel design edge attachment windshield which can be changed out by four maintenance personnel in less than 4 hours with a service life of 4 years or more. Such a design would utilize a two-part channel, or a channel with an additional leg which itself bolts to the aircraft frame. Safe fast cure or tacky tape type sealants could be used.

REFERENCES

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